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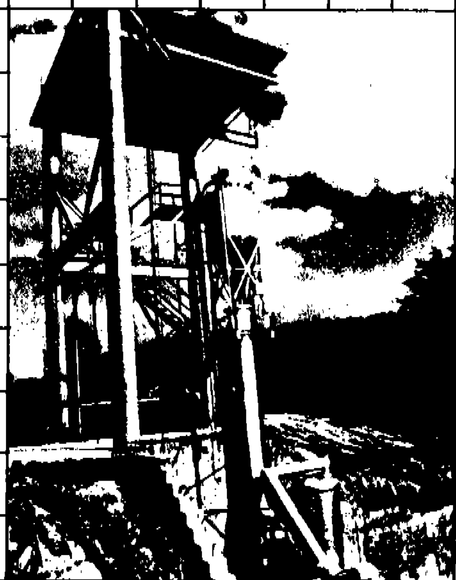
BIOMASS ENERGY TECHNOLOGY ANNUAL TECHNICAL PROGRESS REPORT
VOLUME II, TECHNICAL SUMMARY



Biomass Energy Technology Division
Office of Conservation and Renewable Energy
U.S. Department of Energy

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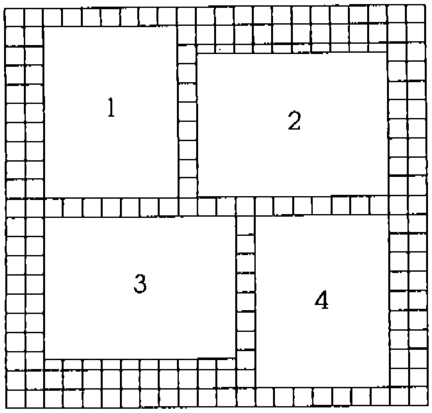

1 Emergent aquatic plants such as cattails are highly productive and represent significant feedstock resources for fuel production. 2 Fundamental research is being performed on the microbiology and biochemistry of digestion cultures to increase methane yields and conversion efficiencies. 3 More than 50 field plots have been established in several geographical areas to allow evaluation of short-rotation intensive culture techniques. 4 Tests at the Aerospace Research Corp. showed that gases from a pressurized wood particle combustor can be used directly to power a gas turbine after cleanup in a series of cyclones.

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II. FEEDSTOCK PRODUCTION RESEARCH

A. DESCRIPTION OF FEEDSTOCK PRODUCTION RESEARCH

Feedstock production research involves studies of the direct use of solar energy stored in biomass materials. These materials include wood, nonwoody plants, plant oils, aquatic plants, and wastes created in the production of food and fiber. Research emphasis currently is on species screening and selection, optimization of planting and growing techniques to maximize yields and growth rates, development of improved harvesting methods, and analysis of net energy production and cost factors. Part II is divided into six sections. Section B is short-rotation woody crops, which describes efforts to increase wood production through the development of new systems for growing wood crops that take advantage of rapid juvenile growth and coppice regeneration. Section C, conventional silviculture, emphasizes the efficient management and recovery of wood resources in existing forest stands. The herbaceous or nonwoody crops discussion (section D) overviews research on plants that have high yields and the ability to grow on arid and marginal lands. Section E, aquatic plants, describes research on water-based plants that have the ability for rapid growth and high yield such as microalgae, macroalgae, emergent, and floating plants. And Section F presents a summary of feedstock production environmental research.

B. SHORT-ROTATION WOODY CROPS

Recognizing the importance of wood as an alternative renewable energy source, DOE initiated the Short-Rotation Woody Crops Program (SRWCP) in 1978, to examine the potential for short-rotation intensive culture (SRIC) across the country and to improve the biological productivity and economic efficiency of dedicated tree-growing systems. Prior to the SRWCP, experience with SRIC in the United States was limited to a few species of trees on a few types of sites. The SRWCP was designed to provide baseline information about short-rotation biomass production for a much larger range of species and sites, and to begin the research needed to accurately assess and improve the productivity and efficiency of developing SRIC systems. To make growing wood for energy feedstocks through short-rotation intensive culture (SRIC) attractive to the private sector, research must increase productivity rates and reduce production costs. Ultimate goals call for approximately 44 dry tonnes/ha-yr at $1.50/million Btu (1983 dollars). It is expected that 26.4 dry tonnes/ha-yr at $2.00/million Btu can be attained in the next decade.

Short-rotation intensive culture relies on dense spacings of fast-growing hardwood species on well-prepared land, using fertilizers, herbicides, and other agronomic techniques to maximize the growth rate of the trees and shrubs. In contrast to conventional forestry, which commonly carries investments 25 to 30 years before realizing any return, the closely spaced trees in SRIC are harvested every 3 to 10 years to capitalize on fast early growth and to realize early return on investment. Replanting costs are avoided by encouraging stumps to resprout vigorously. Reestablishment by stump sprouts (coppice growth) is a key aspect of short-rotation production. It saves time, money, and energy but does place restrictions on the types of trees that can be used. Hardwoods (deciduous trees) and shrubs generally grow much better from stumps than softwoods (conifers) do.

The overall objective of the SRWCP is to develop systems for short rotation that produce woody biomass for energy at competitive prices. Reaching this objective first requires studies to determine the productivities now attainable in SRIC systems, then additional research to determine potential productivities of improved short-rotation systems and to develop the techniques and planting stock needed to reach those potentials. The general objectives of the three major research areas, species selection, stand management, and economic studies, all contribute to reaching the overall program objective.

The objective of the species selection research is to improve the productivity of SRIC through species screening and the testing, selecting, and developing species and strains of trees and shrubs for use in intensively managed systems.

The objective of the stand management research is to improve the productivity and decrease the costs of short-rotation crops by developing effective and efficient techniques for short-rotation stand establishment and management.

The objective of the economic studies is to increase the cost efficiency of short-rotation culture by integrating economic considerations into system design and research planning.

The SRWCP, now in its fifth year, is already providing a comprehensive, consistent data base on short-rotation intensive culture. It is now possible to draw some conclusions about successful stand establishment and early production rates from the results of SRWCP research. A large number of experimental plantings were harvested for the first time in 1981 and 1982. The SRWCP data base will be even more valuable as these plantings mature and their resprouting and regrowth rates are recorded and compared. All SRWCP research is designed to yield information for a national assessment of the potential of short-rotation culture for producing woody biomass for energy.

After five years of research, some conclusions can be drawn about the short-rotation intensive culture concept.

- Fertilizers and weed control are generally mandatory for ensuring the success of short-rotation woody crops, but irrigation is usually not cost effective.
- Improved stand establishment techniques can ensure successful survival (>75%) in 95% to 100% of plantations where species type is adapted to site conditions, and mass propagation of hardwoods by tissue culture has been demonstrated for a few species.
- Intensive management cannot entirely overcome the drawbacks of poor site quality. This is becoming most apparent in the South where SRIC production estimates have not reached predicted levels on poor sites.
- Immediate productivity gains from selection and management studies can still be expected in the Subtropics and Southwest, and longer term gains from genetic studies are expected in all regions. Potential improvements in productivity through careful selection of planting stock are greater than first believed. Results indicate that the average productivity of short-rotation stands can be doubled by selecting appropriate varieties and species.
- The spacings and rotation lengths that maximize productivity are not necessarily the most cost effective. Economic costs of planting and harvesting must be factored into decisions regarding spacing and harvest cycle.
- The economics of SRIC are significantly affected by productivity levels, the costs of harvesting and transporting, the risks of crop failure, the lack of a developed distribution market for biomass fuels, and competition for markets (alternative fuels) and for land (fiber and food crops).

Figure 2-1 shows how the three major research areas are coordinated so that all information produced by the SRWCP will contribute to achieving the overall program objective by 1987.

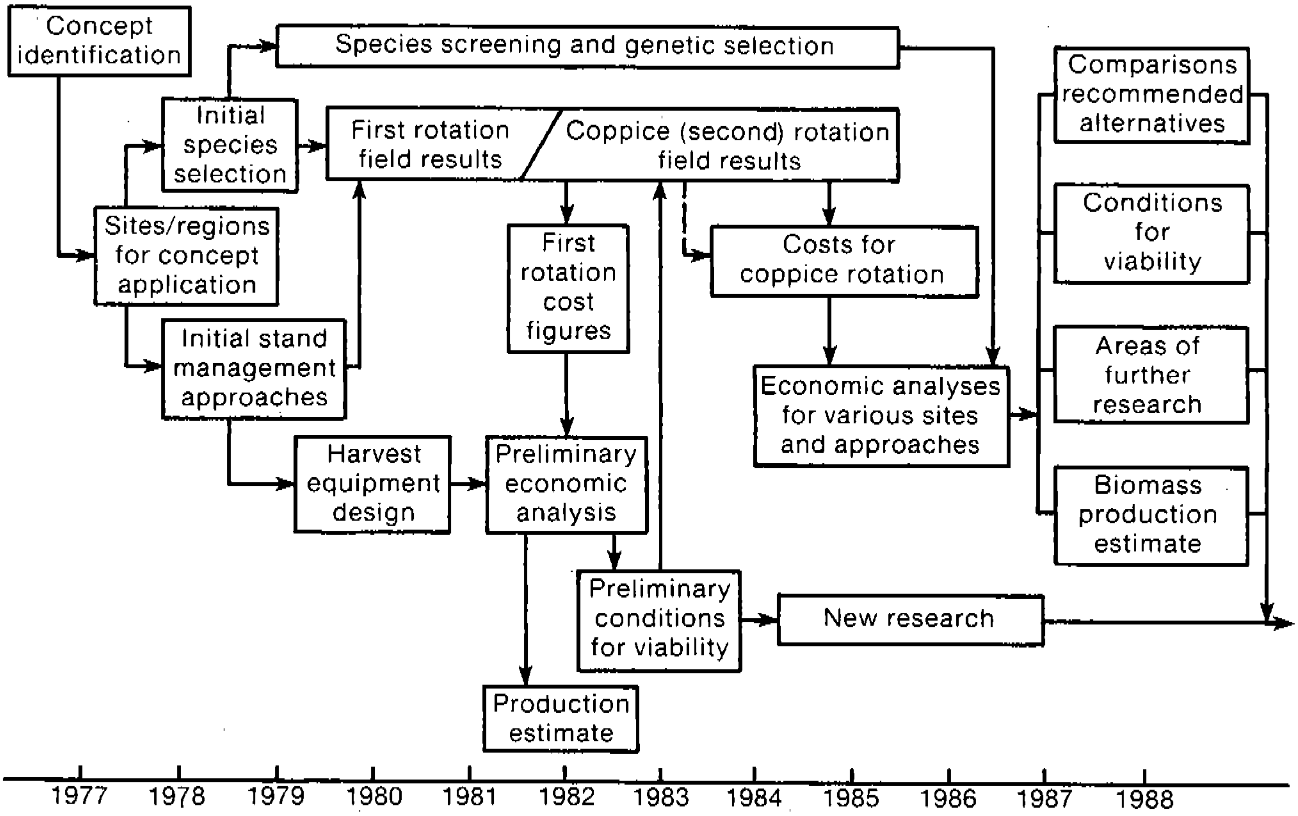

Fig. 2-1. Meeting the Short-Rotation Woody Crops Program's overall objectives depends on information flow among the major research areas

1. Species Selection Studies

The SRWCP species selection studies are designed to improve the productivity of short-rotation systems by identifying the best trees and shrubs to use as planting stock. The research includes studies comparing numbers of different species, studies looking for superior strains of a single promising species, and studies examining hybrids between species. In general, species selection begins with screening trials comparing more than one species. When the most promising species have been chosen, the next step is to examine their natural variability to determine how much improvement could be gained by additional selection. If variations do exist, selection studies to choose individuals and strains with desirable characteristics for propagation and large-scale testing can follow. The four objectives of the SRWCP selection studies can be considered steps in this sequence of studies:

- identify the best woody species for short-rotation systems in each major region of the United States that appear to have potential for supporting SRIC;
- define the genetic diversity within promising species to identify the possibilities for further improvement;
- select strains within species or hybridize species for traits valuable in short-rotation systems; and
- test the selected species, strains, and hybrids for production under intensive management on a range of sites.

The SRWCP selection work is at different stages in different regions and different projects. Many species that appear to be suitable for short-rotation culture have never been grown under intensive management. When these are tested for the first time, it is usually in selection trials comparing several different species. In the SRWCP, most projects making such species comparisons test the same species on several different sites. Many hardwoods are quite sensitive to site characteristics. Because all regions contain a variety of sites, no single species is likely to be best for an entire region. The SRWCP is intended to produce an overall picture of the prospects for short rotation, and testing a variety of sites in each major region simultaneously is the fastest way to reach that goal.

Genetic improvements represent a relatively advanced stage in short-rotation intensive culture research. They offer considerable promise for long-term improvements in SRIC productivity. In FY 1982, one of the objectives was to improve productivity of several species by 30% over unselected stock. The results showed that the average percentage of improvement over unselected stock was 55.5, which was 25% greater than expected. This illustrates the potential productivity increase that could result in the first generation from using selected stock. For the most part, actual selection, propagation, and testing of superior clones or strains for a variety of SRIC species have not yet taken place.

The earliest studies on SRIC were performed on sycamore in the South and Southeast in the 1960s. Even earlier, the U.S. Department of Agriculture began selecting hybrid poplars for a variety of uses, primarily in the Northeast. In such cases, the SRWCP tried to build on the past work and began directly with studies examining the potential for improving the selected species.

All the selection studies in the SRWCP in 1982 are described below. Many are species screening studies, but others are genetic studies of a single species or a group of hybrids between species.

The University of Alaska is evaluating selected hardwood species for intensive biomass production on a range of sites in interior Alaska. Six native species, chosen in 1981, were established on three sites in the state, and species/site interactions were addressed. Genetic variation within each species will be examined to identify potential production improvements. In addition, selected species are being evaluated for chemical defenses against browsing by small mammals. Attempts are being made to produce hybrids between the black cottonwood and the native balsam poplar (*Populus balsamifera*).

The University of Arizona has prepared a comprehensive literature review on woody plants in the semiarid Southwest to identify the most promising species for biomass production in this region. The project will test three or four of these species. Selection will be based on productivity, site adaptability, ability to coppice, and resistance to pests and diseases. Field tests were established in 1982 at three sites using Prosopis spp. and Acacia spp.

Michigan State University has been evaluating more than 20 species for biomass production on a range of sites throughout the state since 1979. To date, several promising species [European black alder (Alnus glutinosa), hybrid poplar, and hybrid pine (Pinus nigra x P. densiflora)] have been identified, and species/site interactions have been investigated. Guidelines for plantation establishment and management are being developed for cutover sites and old fields. Additional project emphasis is on genetic improvement.

The University of Minnesota is evaluating the potential of peatland areas for woody biomass production. Domestic and imported species of willow, alder, and poplar are being investigated for their adaptability to the northern environment and as a short-rotation crop. This research includes the macropropagation (cuttings) and micropropagation (tissue culture) of these species. To date, more than 6000 willow plantlets have been propagated via tissue culture. An additional 15,000 willows have been propagated by cuttings, including several species which have been very productive in European studies. A 1-ha nursery and 5 ha of field plots have been established on which willow species are being screened, and spacing and cultivar trials are being conducted.

Mississippi State University completed a study of genetic selection in American sycamore for biomass production in the mid-South in 1982. This project identified genetically superior seed sources in specific geographic subregions in Mississippi and adjoining states. In general, significant differences in survival, disease resistance, and yield were noted. It was determined that a 22% increase in biomass yield per hectare can be obtained by using the best performing families from the specific subregion within the area, and a 17% increase can be obtained by using the overall best families for all geographic subregions. The significance of this research is that it indicates the existing genetic variability for biomass productivity for this species and location and provides a basis for evaluating what further improvements can be achieved through genetic manipulation.

Texas A&I University is investigating production of woody biofuels from mesquite. Mesquite is a leguminous woody shrub indigenous to tropical and subtropical arid and semiarid regions. This project, which started in 1981, is using clonal stock from 20 shrubs that were previously identified as promising for woody biomass production. The goal of this project is to evaluate the use of these high-producing strains for cost-effective biomass energy production in the semiarid Southwest. Research efforts include determining the biomass production of selected clones under field conditions, collecting additional plant material from unusual sources and origins, and refining tissue culture techniques and propagation methods. By the end of 1982, a tissue culture laboratory was established, and 12 ha of field trials were planted.

The USDA Forest Service's Pacific Northwest Forest and Range Experiment Station is evaluating red alder for the SRWCP. The project is a multidisciplinary research effort to determine the cultural requirements of red alder, examine the genetic variation of the species, and assess the productivity of sites in the Pacific Northwest for short-rotation alder plantations. Figure 2-2 shows red alder seedlings from different native populations being compared on a series of different soils. Red alder is a promising species for biomass production because it fixes nitrogen, grows rapidly, and adapts to a variety of soil and site conditions. To date, silviculture research in the Pacific Northwest has focused on conifers and black cottonwood, and little is known about red alder. The information gained from this SRWCP research effort will be used to increase the yield, cost-effectiveness, and energy efficiency of red alder biomass plantations.

Fig. 2-2. Red Alder (*Alnus rubra*) seedlings from different natural populations are being tested on a series of soil types in a Short-Rotation Woody Crops project at the Pacific Northwest Forest and Range Experiment Station

Utah State University studied six native shrubs for biomass production on arid and semi-arid lands of the Southwest. Biotypes from a variety of native shrub populations were selected, propagated, and established on dryland sites in Utah. The following conclusions resulted from this research: biotypes of shrub species must be grown in areas where they are adapted, further study is needed to determine the optimum rotation length, and substantial productivity rates can be achieved (5.2 dry tonnes/ha-yr) from shrubs grown at close spacings and with minimal management on dry sites.

The University of Vermont is evaluating the feasibility of short-rotation intensive culture of selected hardwood species on marginal agricultural lands in the Northeast. Since this project began in 1979, 15 different hardwood species and 7 clones of hybrid poplar have been screened for biomass production on a variety of sites in Vermont and northern New York. Various weed control methods, fertilizer levels, and management techniques are being evaluated. To date, the most promising species at most sites are hybrid poplar and black locust. Additional efforts include a study of the economic feasibility of short-rotation culture in the Northeast and an assessment of coppice regrowth.

The University of Washington and Washington State University are studying the genetics of black cottonwood for biomass production. The project is identifying genetically superior clones of black cottonwood and black cottonwood hybrids for biomass production. Fifty-five clones are being evaluated for rapid growth, disease resistance, and site adaptability. Mean annual biomass production ranged from 4.7 to 23.2 dry tonnes/ha-yr after three growing seasons. Differences in disease resistance and adaptability to site factors among clones were noted. This study indicates that significant gains in productivity can be achieved through genetic selection and improvement.

2. Stand Management Studies

Stand management studies are improving the productivities and minimizing the costs of short-rotation culture on many kinds of sites by developing efficient techniques for establishing and maintaining SRIC systems. This area of research contains the largest number of individual projects in the SRWCP and covers the largest number of research topics.

In 1982 stand management research was conducted for the SRWCP by 13 different institutions around the United States. Many projects are comparing sites of differing quality within a single region. Therefore, complementary information is being produced that will be important in assessing, adapting, and improving both the economic and biological efficiencies of short-rotation culture in each region of the United States. The information being developed is necessary to evaluate the future role that SRIC systems can play in supplying the energy requirements of the country.

The seven specific goals listed below show that SRWCP stand management research is multidimensional and of a long-term nature:

- develop procedures for the mass propagation of improved planting material;
- develop and improve techniques for ensuring high survival and rapid early growth of newly planted seedlings and cuttings;
- identify the most efficient means for controlling competing vegetation in SRIC;
- determine the most cost-effective systems for using fertilizers in SRIC;

- determine the costs and benefits of using irrigation in SRIC;
- determine the relationships among species, spacing, rotation length, and production in SRIC; and
- determine the major pests and diseases in SRIC systems and develop ways to control them.

Although stand management research also is being conducted in several other studies, the current emphasis of those studies is either species selection or economic analysis, and they are described in other sections of this report. The projects with major emphasis in stand management are described below.

The University of Arkansas, in an SRWCP project that includes cooperative studies with the USDA Forest Service and Georgia-Pacific Corporation, has characterized and quantified understory wood biomass in natural southern pine stands. Forty plots were established in two forest types—pine and pine-hardwood—in southern Arkansas and northern Louisiana. Each type had two density classes (high and low) and two site classes (good and poor). All sites have been harvested, and the data have been collected. The average understory biomass production for all sites is 23.4 dry tonnes/ha with a range of 2.2 to 57.6 dry tonnes/ha. The highest average yield, 32.1 dry tonnes/ha, was harvested from a poor, high-density, predominantly pine site.

The BioEnergy Development Corporation in Hilo, Hawaii, is evaluating eucalypts as a source of biomass fuel. BioEnergy has planted 230 ha of eucalypts (primarily *Eucalyptus saligna*) on the island of Hawaii. Approximately 68 ha are being used for plantation establishment studies including fertilizer, herbicide, and spacing trials. The remaining area is being monitored for economic analysis and for future large-scale harvesting trials. The greatest growth, more than 6.0 m in one year, has been achieved on fertilized sites. Estimates of dry weights range from 6.4 to 11.1 tonnes/ha-yr on a poor site to 13.1 to 24.4 tonnes/ha-yr on the best sites. This project is scheduled for completion at the end of 1983.

The University of Florida is evaluating seven native and exotic woody species for biomass production. This interdisciplinary research effort started in 1978 is scheduled to end in 1983. It includes assessment of land availability, intraspecific genetic selection, species screening, evaluation of cultural treatments and management regimes, and economic analysis of short-rotation intensive culture. A statewide survey of land availability and quality has been completed. To date, eight sites throughout the state have been planted; and data on genetic improvement, fertilizer responses, growth rates, and water use are being collected. An evaluation of differences among 20 *Eucalyptus grandis* progenies, planted on a south Florida site, shows genetic variation in biomass yield. The best progenies are producing more than twice the biomass of the average progenies. Preliminary estimates of biomass productivity of the eucalyptus progenies exceed 13.0 dry tonnes/ha-yr; and with the addition of high nitrogen or phosphorus fertilizers, productivity may exceed 20.0 dry tonnes/ha-yr on selected sites. Although *E. grandis* appears to give the highest productivity levels of all the species examined in Florida, it does not coppice well, and further selection for cold hardiness is necessary.

The University of Georgia is evaluating biomass production of five hardwood species in short-rotation plantations irrigated with municipal sewage effluent. This project is a cooperative effort between the university and the Clayton County (Georgia) Water Authority, which operates the largest land treatment system in the United States devoted to forest production. The goal of this project is to identify the species most suitable for biomass production in the Southeast under the high nutrient and moisture conditions associated with wastewater irrigation. Five species of trees, cottonwood (Populus deltoides), sweetgum (Liquidambar styraciflua), sycamore (Plantanus occidentalis), yellow-poplar (Liriodendron tulipifera), and white oak (Quercus alba), have been planted. The project, begun in 1981, is scheduled to end in 1986.

The University of Georgia is also investigating means of increasing the biomass production in short-rotation intensive systems through species admixtures, fertilization, and cultural practices. Two plantations of 20 ha each have been established on worn-out farmland—one in the Coastal Plain and one in the Piedmont of Georgia. Three- and four-year-old sycamore, black locust, sweetgum, and European black alder on the Piedmont site were harvested. Black locust and sycamore alone or in admixture gave biomass yields ranging from 2.54 to 4.95 dry tonnes/ha-yr. Pure sweetgum produced only 0.70 dry tonne/ha-yr, and European black alder was a poor performer at this site. Plantlets suitable for planting have been propagated in significant numbers for sweetgum and black locust.

The University of Houston is evaluating the Chinese tallow tree (Sapium sebiferum) for intensive silviculture along the Gulf Coast. Stand establishment and cultural practices such as spacing, fertilization, and weed control are being studied. After 4 years of study, fertilizer application was found to be critical to the rate of growth of young trees, and trees planted at close spacings (0.3 m^2/tree) accumulated about two to four times the biomass of wide spacings (1.4 m^2/tree). Productivity in closely spaced, fertilized plots is 9.7 dry tonnes/ha-yr. Direct seeding either by hand or by standard agricultural planters appears to be feasible as a routine practice. After a year of genetic studies, the Chinese tallow tree shows a wide variation in terms of survival and height growth among seed sources. The seed, which has a thick waxy coating, may also prove to be an economical source of high-quality oil.

The University of Illinois is developing a woody biomass production system for small landowners using marginal agricultural lands. The goal of the management system is to provide maximum productivity with a minimum of maintenance and labor. The following strategies are included in the system: use of high-density plantings, short rotations (less than 5 years), no initial fertilization, and irrigation for initial establishment only. After three growing seasons, productivity rates of 9.6 dry tonnes/ha-yr have been achieved in autumn olive plantations grown at a 0.09 m^2/tree spacing with no fertilization and minimal irrigation. Productivity rates for sycamore and eastern cottonwood grown under the same spacing and management conditions were 3.3 dry tonnes/ha-yr. However, production of sycamore at 0.05 m^2/tree was 5.8 dry tonnes/ha-yr.

Kansas State University is determining the biomass yields, financial and energy balances, and herbicide sensitivity of selected hardwood species in short-rotation intensive systems throughout Kansas. Black locust grows well at all sites; cottonwood and silver maple are best suited for eastern sites, and Siberian elm (Ulmus pumila) for central and western locations in the state. The greatest production yields come from (1.2 m x 1.2 m) spacing and till weed control; however, financial and energy costs favor wider 2.6 m x 1.2 m spacings. Several herbicides are effective in controlling the weed population, but mechanical cultivation results in less tree mortality.

Michigan Technological University is determining the feasibility of converting existing pole-size maple stands [sugar maple (Acer saccarum) and red maple (A. rubrum)] to short-rotation plantations using black locust as an interplanted species. Three forested sites, representing high, medium, and low productivity levels, were clearcut commercially. Plots were interplanted with black locust and fertilized with nitrogen, phosphorus, and potassium. Significant differences have been identified in the production of stump sprouts among sites, species, timing of fertilizer applications, and tree diameters. The symbiotic association of black locust with Rhizobium, the nitrogen-fixing bacterium, is being studied. Selected strains of the bacterium may enhance the productivity of black locust. Based on preliminary results, conversion of existing stands to SRIC does not appear promising.

North Carolina State University is screening hardwood tree species and evaluating silvicultural systems for woody biomass production in the Southeast. This research project has been greatly enhanced by cooperative efforts within the North Carolina State University Hardwood Research Cooperative, which is composed of state agencies and 18 forest industries. The cooperative members provide land for field sites, technical support, and equipment. Conclusions to date, based on previous plantings by the Hardwood Research Cooperative, are that sweetgum is the most adaptable hardwood tested, hardwoods must receive intensive care until well established for acceptable growth and development, and species/site interactions must be considered. Four new plantations were established in 1979, 1980, and 1981 to evaluate species/site relationships, spacing, coppicing, and rotation age. Severe drought conditions in 1980 and 1981 demonstrated that many of the hardwood species being tested could not survive the dry conditions.

A Pennsylvania State University project, now in its final year, has evaluated the effect of municipal wastewater irrigation on biomass production in hybrid poplar plantations. An economic analysis of using wastewater as a substitute for inorganic fertilizer is under way. Results obtained to date indicate that wastewater irrigation significantly increased diameter and total height growth of hybrid poplar. Furthermore, total woody biomass production was more than doubled by wastewater irrigation after 5 years of growth.

Seattle City Light, a municipally owned electric utility, is evaluating woody biomass production as a function of soil and site conditions. Two field sites are being used for this study. Both sites are representative of the land available for biomass plantations in western Washington. The first site, located under a power line right-of-way, is a dry, glacial outwash site of comparatively low productivity (Fig. 2-3). The second site is a glacial till site of comparatively high productivity. Productivity rates of red alder on both sites after two growing seasons range from 7.0 to 9.0 dry tonnes/ha-yr at a spacing of 2.2 m^2/tree. There was no significant difference between sites or between fertilized and control plots. Equipment tests with a prototype baler suggest that with modification, a baler could be very competitive with a chipper under SRIC conditions.

USDA Forest Service, North Central Forest Experiment Station, in the final project year, has developed a management program for establishing large-scale poplar plantations. The establishment period, defined as the first three growing seasons, is the most critical period for large-scale plantations. Investigators in this project have identified optimum methods for site preparation, planting, and weed control. Selection of planting materials and initiation of pest management strategies are also being studied. The percentage of successful plantations (those with greater than 75% survival) has risen from 15% in 1977 to 95% in 1980. Current research efforts include comparison of first and second rotation yields. At this time, coppice production is expected to exceed first rotation production

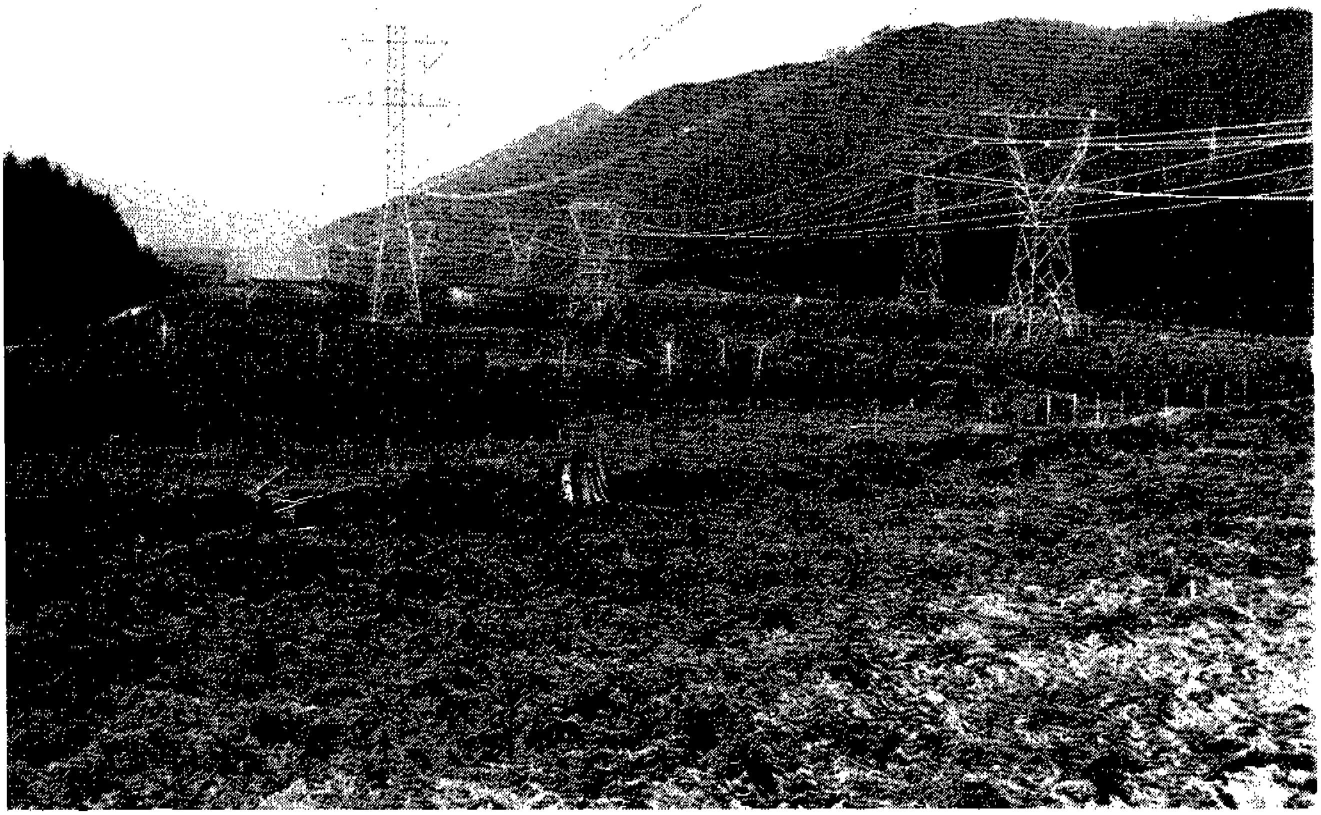

Fig. 2-3. A Short-Rotation Woody Crops planting established by Seattle City Light on a glacial outwash in Washington

rates by 1.5 to 2.5 times. Economic evaluation of the costs of various management strategies will be evaluated after harvest of 3-year-old plantations in the fall of 1982. A risk analysis of plantation establishment is in progress.

3. Economic Studies

Economic Studies is the smallest and newest task in the SRWCP. It evolved from a task called "Harvest, Collection, Transportation and Storage of Biomass" that was part of the original SRWCP in 1978. The economic studies task now includes all SRWCP research designed primarily to produce information for the economic evaluation of short-rotation crops, though not all the studies are, in themselves, economic evaluations.

The major objective of the economic studies in the SRWCP is to increase the cost efficiencies of short-rotation systems by integrating economic considerations into system design and research planning. Four specific goals have been defined for this subject area:

- identify and define the expenses associated with SRIC,

- determine the relative economic importance of the different components of SRIC systems,
- define the critical range of variation for each major economic component of SRIC, and
- determine the site-specific revenue requirements for selected short-rotation woody biomass production systems.

The Biosys Corporation of McLean, Va., is evaluating the availability of land for short-rotation biomass plantations in the western Great Lakes region. This project addresses the following issues: the potential land resource available for biomass plantations, major issues in land competition, the types of sites available for biomass plantations, and the location of potential sites.

Mittelhauser Corporation of Downers Grove, Ill., has developed an integrated computer program that determines the expected cost of woody biomass produced in SRIC systems. The model incorporates the costs of all relevant aspects of short-rotation woody biomass production including land purchase or lease, establishment, development, harvesting, and storage operations. Mittelhauser Corporation is currently working with the SRWCP investigators at the University of Illinois on a series of analyses that will determine the effects of a variety of management practices on product prices for the conditions that exist in Illinois.

The Packaging Corporation of America (PCA), a forest products company in Filer City, Mich., is evaluating large-scale hybrid poplar plantations. To date, PCA is the only large-scale planter of intensive-cultured hardwoods in the Great Lakes region. The company has planted more than 1.5 million hybrid poplars on 1200 ha since 1975. The SRWCP project at PCA is using the existing plantations to determine the economics and productivity rates of large-scale short-rotation plantations. This project also emphasizes the following areas of research: development of soil/site/yield guidelines; evaluation of plantation establishment techniques; evaluation of plantation management strategies, including pest management; and evaluation of poplar nursery management techniques.

The Pennsylvania State University is evaluating the productivity of short-rotation hybrid poplar on two sites, one good and one poor, under four management strategies (control, irrigation, fertilization, and irrigation/fertilization). Data also are being collected on the energy and economic inputs needed to operate and maintain the plantation under each management strategy. The investigators are completing a linear programming model that will analyze and compare the energy and economic data for the different site/management combinations.

Virginia Polytechnic Institute and State University (VPI), Blacksburg, Va., is designing and building the prototype of a harvesting system to sever, collect, transport, and process woody material from short-rotation energy plantations. The system is designed for flexibility in harvestable tree size, operable terrain, and road spacing. It will be able to handle single stems from a seedling planting and multiple stems from coppice development. VPI's harvesting system mounts on a large tractor or other base carrier that can also be used for spraying, fertilizer application, and other management activities. Standard, carbide-tipped, circular saws are used for severance, and the harvested material is captured by two banks of opposing vee belts.

C. CONVENTIONAL SILVICULTURE

Wood is considered to have the greatest potential in biomass energy development over the next few decades. The USDA Forest Service estimates for the total green weight of the Nation's aboveground tree biomass are 32.6 billion tonnes with 15.4 billion tonnes in softwoods and 17.2 billion tonnes in hardwoods. Within this biomass volume are an estimated 544 million tonnes (roughly equal to 1088 million green tonnes) of biomass that are not now used for other purposes and could be available annually for energy where economically feasible. These 544 million tonnes of biomass are equivalent to 1.36 billion barrels of oil.

The objective of this USDA Forest Service program is to conduct research and development activities aimed at increasing productivity, availability, and recovery of wood that are technically, economically, and environmentally acceptable for energy applications in the near term. The production systems include assessment, growth, harvesting, storage, and delivery.

Specific objectives were developed to address three goals. The first was to develop biomass assessment methods for developing standardized procedures for obtaining biomass statistics, provide an initial compilation of national biomass statistics, and evaluate existing equations and prepare tree volume and weight tables. The second was to investigate management options for multiproduct and energy use of biomass in unmanaged siliviculture stands as well as hold regional workshops on wood lot management. The third goal was to evaluate available harvesting and chipping systems for residue recovery, timber stand improvement, and salvage operations as well as to evaluate available in-woods processing systems.

1. Wood Biomass Assessments

The State University of New York (SUNY) is developing methods to sample trees and construct biomass tables for use with regional forest inventories. This program was separated into two related components. First, SUNY took the equations and tables available in the literature and made a regional estimator that could be applied throughout the Northeast. In this way, the existing estimators could be analyzed, and a statement could be made relative to the conditions under which the individual estimators could be applied. A forest population could then be constructed from which to draw samples (phase 1). Once a computer simulator program was developed (phase 2), samples could be drawn from the theoretical population. These sampling designs would be analyzed in a third phase to determine their application in the construction of biomass tables.

The biomass, nutrient, and energy contents of southern hardwoods are being analyzed by the Southeastern Forest Experiment Station and North Carolina State University. Fully stocked hardwood stands in the Gulf and Atlantic Coastal Plain, growing on bottomland, swamp, and wet flat sites, have been sampled. In the Piedmont, fully stocked stands growing on bottomland and upland slopes and ridges are being sampled.

At each sample location all trees at least 12.7 cm diameter at breast height (d.b.h.) on a 0.04-ha plot are felled and measured; and abovestump total tree and tree component (stem and crown wood, bark, and foliage) green and dry weights are determined. Biomass is also determined for all trees 2.5 to 12.4 cm d.b.h. on an 0.008-ha subplot taken at the center of the 0.04-ha plot. Biomass of understory vegetation is determined on microplots located in the stand. Wood, bark, and foliage samples from each tree sampled are analyzed to determine moisture content and specific gravity. Samples from each tree are shipped to North Carolina State University for caloric and nutrient (N, P, K, Ca, Mg) content determination.

The location of the biomass plots and the cooperator conducting the field work are listed in Table 2-1 by site type and age class for the Coastal Plain. Data were collected on 1415 trees (d.b.h. range 2.5-59.9 cm) representing 37 Coastal Plain species. Fifteen species were sampled sufficiently for biomass equation development. This represents 80% of the commercial hardwood volume in the Coastal Plain.

Average actual total tree above stump and tree component green and dry biomass production per hectare by site type and age class are presented in Table 2-2 for the Coastal Plain plots.

Table 2-1.
Location of the twenty five 0.04 hectare hardwood biomass plots established in the Coastal Plain and cooperator collecting field data

Age Class (Years)	Site Type		
	Bottomland	Wet Flat	Swamp
10	Sumter Co., Ala. American Can Corp.	Duval Co., Fla. Container Corp.	Columbus Co., N.C. Georgia Pacific Corp.
	Bertie Co., N.C. Georgia Pacific Corp.	St. Johns Co., Fla. Container Corp.	Florence, S.C. Georgia Pacific Corp.
20	Warren Co., Miss. International Paper Co.	Taylor Co., Fla. Buckeye Cellulose Corp.	Nassau Co., Fla. Rayonier, Inc.
	Sumter Co., Ala. American Can Corp.	Dorchester Co., S.C. Westvaco Corp.	Glynn Co., Ga. Brunswick Pulp Land Co.
40	Dallas Co., Ala. Hammermill Paper Co.	Washington Co., Ala. Scott Paper Co.	Craven Co., N.C. Weyerhaeuser Corp.
	Southampton Co., Va. Union Camp Corp.	Taylor Co., Fla. Buckeye Cellulose Corp.	Hertford Co., N.C. Union Camp Corp.
	Marion Co., S.C. International Paper Co.		
60	Wayne Co., Miss. Scott Paper Co.	Craven Co., N.C. Weyerhaeuser Corp.	George Co., Miss. Masonite Corp.
	Escambia Co., Fla. St. Regis Paper Co.	Jasper Co., S.C. Continental Forest Ind.	Taylor Co., Fla. Buckeye Cellulose Corp.

Table 2-2.
Summary of actual total tree abovestump biomass of an age series of natural, even-aged hardwoods on bottomland, wet flat, and swamp sites in the Coastal Plain of the southern United States

Age Class	Sapling Trees	Pulpwood and Sawtimber Trees: Stem to 10.2-cm Top	Crown[a]	Total Tree	All Trees ≥2.5 cm d.b.h.
Years			Green (dry) tonnes/ha		
			Bottomland		
10	78.6(43)	—	—	—	78.6(43)
20	57.3(27.1)	189(86.9)	64.3(29.6)	253(117)	310(144)
40	26.9(14.3)	259(143)	89.2(48.6)	349(192)	375(206)
60	32.9(18.8)	308(166)	79.5(44.1)	387(210)	420(229)
			Wet Flat		
10	84.5(43.5)	—	—	—	84.5(43.5)
20	116(65.9)	26.2(13)	15(7.6)	41.4(21)	157(86.9)
40	7(3.6)	173(105)	59.8(35.8)	232(141)	240(144)
60	21(11)	422(215)	109(55.8)	531(270)	552(282)
			Swamp		
10	78(38)	2.2(1.1)	2(1.1)	4.3(2.2)	82.2(40)
20	136(74.8)	35.4(20)	21(11)	56.7(30.5)	192(105)
40	60.9(32.3)	245(132)	91.4(45.9)	336(178)	397(211)
60	17.3(9.6)	474(235)	105(52.6)	580(288)	597(298)

[a]Crown—includes all branches, foliage, and stem topwood.

The proportion of total tree stand biomass per hectare in sapling size trees and larger is shown in Table 2-3 for the three site types sampled in the Coastal Plain by age class. The proportion of stand biomass per hectare in saplings decreased with increasing stand age from 94% to 100% in the 10-year-old stands to 3% to 8% in the 60-year-old stands for all sites.

Average annual total tree biomass production per hectare for the three site types sampled in the Coastal Plain is presented in Table 2-4 by age class. The average total tree biomass production per hectare per year was relatively uniform across all sites and age classes except the 20-year-old bottomland sites. Average annual biomass production ranged from 3.6 to 5.4 dry tonnes/ha across all sites and age classes compared to 7.2 dry tonnes/ha for the 20-year-old bottomland sites. Annual dry biomass production per hectare averaged 5.2 tonnes on the bottomland sites, 4.3 tonnes on the wet flat sites, and 4.9 tonnes on the swamp sites.

Table 2-3.
Proportion of total tree biomass per hectare in sapling trees[a], crown[b], and stem[c] for an age series of natural even-aged hardwoods on three site types in the Coastal Plain

Age Class	Proportion of Total Tree Biomass per Hectare		
	Saplings	Crown	Stem to 10.2-cm Top
Years		Percent	
		Bottomland	
10	100	—	—
20	19	20	61
40	7	24	69
60	8	20	72
		Wet Flat	
10	100	—	—
20	76	9	15
40	2	25	73
60	4	20	76
		Swamp	
10	94	3	3
20	71	10	19
40	15	22	63
60	3	18	79

[a]Trees 2.5 to 12.4 cm d.b.h.

[b]Includes branches, foliage, and stump topwood of tree ≥12.7 cm d.b.h.

[c]Includes stem 12.7 cm d.b.h. and larger.

Table 2-4.
Average annual total tree biomass production per hectare for an age series of natural even-aged hardwoods on three site types in the Coastal Plain

Age Class	Site Type		
	Bottomland	Wet Flat	Swamp
Years	Green (dry) tonnes/ha-yr		
10	7.8(4.3)	8.5(4.3)	8.3(4.0)
20	15.5(7.2)	7.8(4.3)	9.6(5.4)
40	9.4(5.2)	6.0(3.6)	9.9(5.4)
60	6.9(3.8)	9.2(4.7)	9.9(4.9)
Average	9.9(5.2)	7.8(4.3)	9.4(4.9)

Aboveground biomass volume growth and yield of slash pine are being studied by the Southern Forest Experiment Station. During FY 1982 field plots were established in slash pine stands over a wide range of sites, ages, and stand densities in both planted and direct-seeded stands. From these plots, 475 sample trees were selected, felled, measured, and weighed in the field. (See Figs. 2-4 and 2-5.) Wood, bark, and foliage samples were collected and taken to the laboratory where green and dry weights, volume, specific gravity, and moisture content were determined.

Existing tree taper models, previously used to predict volumes, will be modified to predict biomass. New models will be constructed if necessary. The tree models will then be used with plot data to estimate volume and biomass yields per hectare for different ages, species, sites, and management practices.

The North Central Forest Experiment Station is projecting future supplies of biomass for energy in the North Central United States. STEMS, the Stand and Tree Evaluation and Modeling System, which has been developed and tested for the forests of the Lake States region and is being extended to include the Central States forests, can project in detail the future growth and development of the forest resource in response to alternative management practices. Incorporation of a biomass estimation framework and separately developed biomass models will allow estimation of biomass and annual change in biomass for any time period for any stand condition found in the region and for any specified management scheme.

Three different diameter growth prediction models were fitted to data for seven Central States species. Two models were from the literature; the third was designed specifically as part of this study. Analyses of the accuracy and bias of the predictions from each of the three models showed that although the models differed markedly in their formulation, they have substantially equivalent predictions of tree diameter and basal area growth for a 10-year interval. Other models were developed to predict current crown ratio and probability of mortality for Central States species.

Fig. 2-4. Weighing branches after removal of twigs and foliage

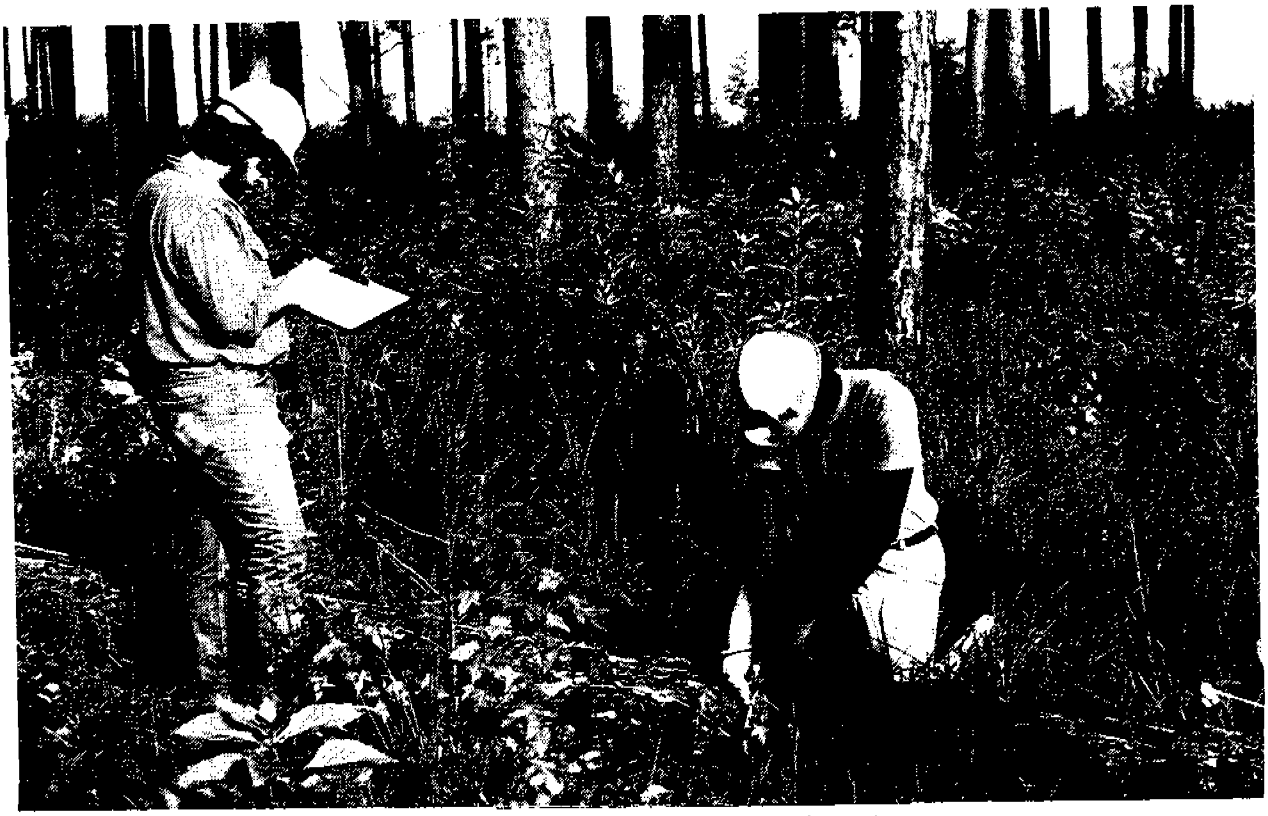

Fig. 2-5. Measuring main stem at 1.5-m intervals

Four management schemes were developed for four different types of trees in the Central States: Eastern red cedar, elm-ash-cottonwood, pin oak, and shortleaf pine/oak pine. In addition, the Lake States upland hardwoods schemes were reviewed from a Central States perspective. Using these schemes, STEMS can project and report biomass produced under different management plans.

TWIGS, The Woodsman's Ideal Growth Projection System, uses the STEMS growth and mortality equations to allow detailed examination of growth and yield (biomass) for individual forest stands. Flexible management routines and a simple economic evaluation provide the capability via the microcomputer for examining changes in biomass production due to altering the management practices, thereby expanding greatly the user group.

2. Natural Stand Management

Extensive coppice production in natural upland hardwood stands of the Southeast is being studied by Duke University. Six stands were chosen for study—four located in the Bent Creek Experimental Forest and two nearby in the Pisgah National Forest. These stands were selected because they met the biological constraints described in the study design, were below 1068 m in elevation (most likely to have hardwood accessible for early removal), and had additional available data because of other Forest Service studies.

Field observations during data and sampling collection were encouraging. Most stands visited had 49,000 stems/ha or more early after clearcutting. Since mature commercial sawtimber stands of this type have only several hundred stems per hectare, approximately 47,000 stems/ha or more are potentially available for energy use without depletion of stems necessary for commercial timber management. Economic harvesting constraints will dictate how much of this biomass can be removed.

At Clemson University studies of the regrowth potential of extensively managed low-grade coppice hardwood stands on upper Piedmont sites are being carried out.

The basic approach to evaluate regrowth of cutover upland hardwood stands is to locate and measure a large sample of coppice hardwood regrowth as it currently exists throughout the Piedmont, on as many sites as practical. The focus is on examples of hardwood stands that have been cut over, preferably clearcut commercially, within the past 20 years and have been left to regenerate naturally without further treatment. Although annual increment of fuelwood products probably does not culminate in less than 20 years, except possibly on the poorest sites, it is expected that in practice sustained yield operations will use rotations no longer than this period.

Site data also include topographic position, aspect, surface drainage, and soil profile information from auger borings on each of the four subplots. The Soil Conservation Service soil-mapping unit and soil series were determined by a combination of reference to the soil survey for the county in which each plot is located and observations on the plot itself.

The preliminary results indicate that wood volume production is maximized before 30 years on poor sites but continues at maximum rates to age 40 on intermediate and good sites. The same general relationships hold for green weight production. Poor sites at 30 years support about 140 m^3 or 202 tonnes/ha. Poor site production has slowed by age 30, so that the differential between good and poor sites becomes far greater at ages beyond 30 years.

The early results suggest that hardwood biomass for energy produced on poor sites can be grown on 20- to 30-year rotations for maximum yields. The large root systems that support the sprout stems permit very rapid early growth but do not sustain high production beyond 20 years on poor sites. A realistic production figure for green biomass on 25-year rotations for hardwood coppice stands on poor sites seems to be 90 to 112 tonnes/ha. The best sites produce twice this yield at age 25, but coppice stands of such high production should be carried to age 40 for maximum sustained yields.

SUNY College in New York and the Northeastern Forest Experiment Station are looking into biomass harvesting systems for private nonindustrial forests (Fig. 2-6). A computer program (HARDAT) was developed by project scientists to analyze the data being collected in order to evaluate harvesting equipment and systems that are currently available. HARDAT is a HARvesting DATa base system that describes an operational harvesting system, the conditions in which it operated, the products obtained, and the production and costs of each harvesting function and the total system. The data stored have actually been experienced; theoretical performance is not entered into the system.

The HARDAT control cards are put into the Statistical Analysis System (SAS) program developed at North Carolina State University. All the analytical techniques of the SAS program are available to the HARDAT data base. The HARDAT system is operational at both SUNY and West Virginia University.

Fig. 2-6. Logging small-size timber with the Forest Ant

3. Harvesting and Chipping

An investigation of procurement, harvesting, drying, transportation, and storage of woody biomass is being carried out at Virginia Polytechnic Institute. The objective of this activity is to develop a method for transporting entire aboveground portions of both pine and hardwood stems to a mill or centralized processing point in a form compatible with truck, trailer, rail, and barge hauls and with sufficient bulk density to optimize load sizes on the various carriers while expending a minimum amount of capital and energy on in-the-woods operations.

Baling or compacting the material into rectangular cubes offers several apparent advantages (Fig. 2-7). Baling and compacting have been used on a wide variety of material types by a diverse set of industries.

The continuation of the development of the in-woods baler includes (1) design, fabrication, and testing of an inverted grapple in-feed system; (2) adaptation and testing of commercial automatic tying systems for bundling of bales; (3) modification of the control system to provide automatic cycling of feeding, compacting, and shearing of the logging residues; (4) changes to the hydraulic system consisting of a multiple pump drive and variable flow, 170 L/min pump; (5) baler testing at several field locations; and (6) recommendations for the next phase of development.

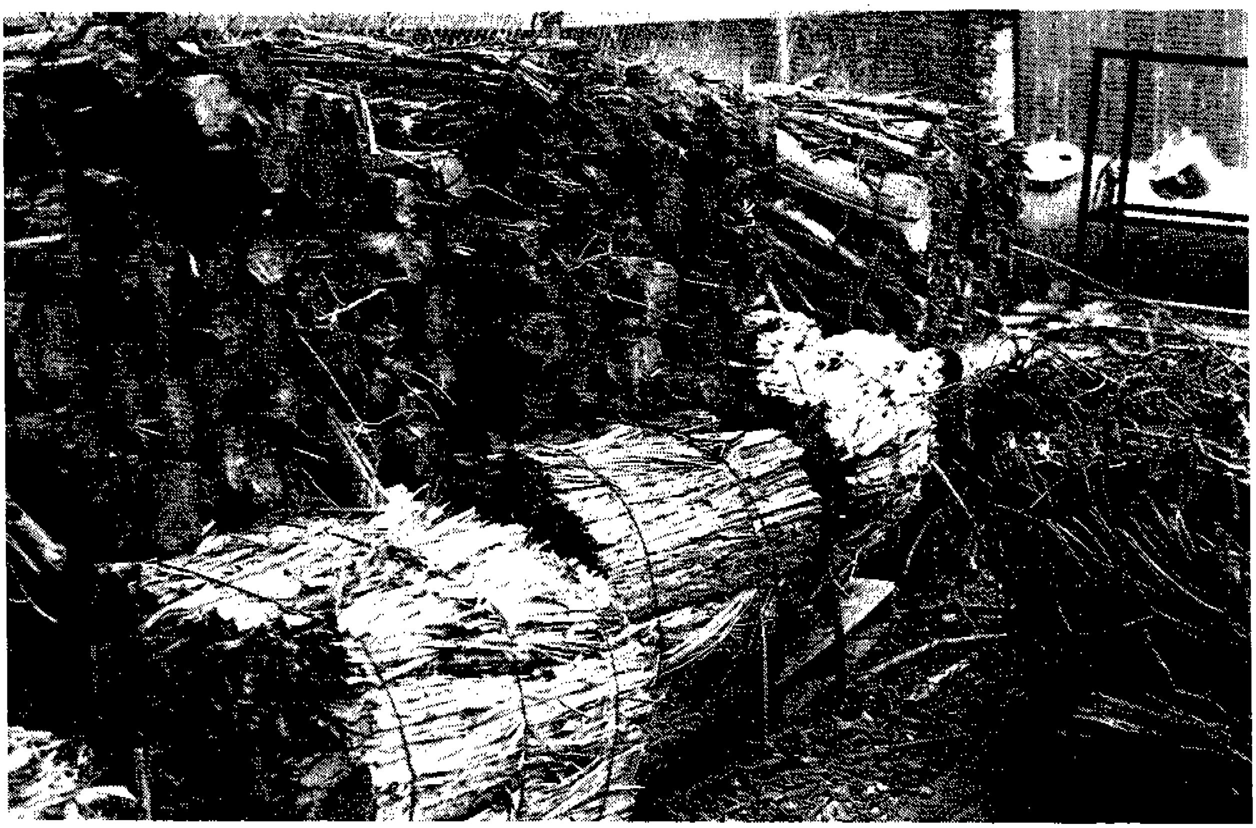

Fig. 2-7. A prototype baling system developed by Virginia Polytechnic Institute achieved a rate of 4 to 5 bales/h

During field tests to bale residues from thinnings and cleanings, a high capacity hydraulic system was installed. This system reduced the average shearing time per bale from 16.1 to 8.0 min. The baler was returned to VPI in early 1982, and an automatic baling system and a larger hydraulic oil tank were installed.

The Southern Forest Experiment Station at Auburn, Ala., is assessing the Nicholson-Koch mobile chipper on selected sites throughout the South, including pretreatment and post-treatment evaluation by company foresters at each location. Pretreatment evaluation consists of photographs and small plot measurements of standing and downed material by size, class, and species. Data on chip production per unit of time and hours of operation are being maintained on a continuous basis. Post-treatment evaluation includes measurements of wood waste remaining on site after the chipping operation.

Construction of two chip collector/forwarders and a utility/transfer machine, and modifications to the Mobile Harvester were completed in July 1982. Mobile Harvester modifications included redesign of the collector frame; modification of the chip discharge chute; redesign of the track tensioning brackets and rams; addition of a communication system between the chipper and forwarders, using both lights and radios; and installation of a cab air-conditioning system.

Two test sites were selected on International Paper Company lands near Mobile, Ala., and a cooperative agreement was established for testing the system. Since mid-September 1982, system performance has been improving steadily. This can be attributed to increasing capabilities of the operators and improved machine availability from both the mechanical and hydraulic systems standpoints. Also, a change was made in the system for unloading the chip forwarders. The first prototype machine required between 20 and 30 minutes to unload a chip forwarder (Fig. 2-8). This long unloading time required that the Mobile Chip Harvester be stopped (delayed) because the second forwarder was filled before the first one was completely unloaded (Fig. 2-9). In an effort to decrease the forwarder unloading times, the chip bucket was reduced in size, and the shortened chip bucket was installed on a self-propelled loader. This combination decreased unloading times to between 15 and 20 minutes.

The average time to fill a chip forwarder to about 5.4 tonnes of chips was 20 to 25 minutes on sites containing an estimated 11.3 tonnes of green biomass/ha, mainly in large standing hardwoods.

Development and field testing of wood residue delivery systems are being done at the University of Idaho. Given the need to establish relative production efficiency and operational feasibility of alternative residue recovery systems, this study was initiated to field test a number of forest residue recovery systems. An integrated system may include compatible subsystems for (1) felling and/or bunching; (2) yarding or skidding; (3) sorting, processing, and loading at the deck; (4) transporting; and (5) preprocessing the residue component into some desired fuel form. Different combinations of subsystems make up the major systems being field tested under various physiographic and timber stand conditions in the Rocky Mountain area (Fig. 2-10).

Production tests involve the application of specified equipment or systems to recover residues under a carefully selected and defined set of circumstances. Detailed time and motion data are accumulated to determine production rates for each component of the system being tested and to determine causes of system delays or malfunctions.

Production tests do not cover all residue and terrain situations that could be encountered, but do treat those conditions that are likely to be most prevalent in the Rocky

Fig. 2-8. Chip unloader and chip forwarders in operation

Fig. 2-9. Chip harvester and forwarder in operational test near Mobile, Ala.

Fig. 2-10. A typical example of collectible forest residue from mortality and logging operations

Mountain area. Production tests also include intensive pre- and post-operation inventories that accurately assess the residue volumes available and proportion of volume actually recovered by each system.

The State of Vermont is investigating the usefulness of cable yarder harvesting in the Northeast. The study methods and data collection include (1) pre- and post-stand inventory analysis, (2) time and motion studies, (3) residual stand damage analysis, (4) production capabilities analysis, and (5) systems cost analysis.

A cable yarding machine is being demonstrated on a variety of sites under different ownerships. Sites selected provide excessive slope (25% or more), rough terrain, both uphill and downhill angles, and an opportunity for logging in all seasons.

A prototype cable yarder, consisting of a double drum winch and a custom built 5.2-m tower mounted on a 35-hp tractor, was designed for this operation by the Department of Forests, Parks, and Recreation and a contractor. The yarding system has been demonstrated to more than 700 attendees at five locations in Vermont. The USDA Forest Service has been conducting a time study and has measured each piece of wood removed at several of these sites.

The New Hampshire Department of Resources and Economic Development is making an assessment of biomass harvesting systems. Optimizing the management of New Hampshire forests, especially the small private woodlands, requires social, silvicultural, and economic rewards to the owner. Total use of woods waste—tops, other merchantable parts of traditionally harvested trees, and cull trees—for energy and other operations is an essential ingredient of the program to convince small private owners to manage their woodlands properly. The Division of Forests and Lands, in cooperation with the University of New Hampshire Cooperative Extension Service, is demonstrating proper biomass operations as well as the economic justification for such forest utilization.

Approximately 89 ha of forest land have been harvested in this project. The timber types, age classes, and topographical conditions are varied, and information is complete on 77 ha of operations. Several conclusions have been drawn from the analysis of the study areas:

- Whole tree logging operations are a feasible concept in stands where light or medium reduction of the basal area is desired.
- Skid trail design and layout is an important part in whole tree operations to reduce damage to residual stems.
- Yard layout requires at least 0.16 ha in single tree species utilization and 0.3 ha in multiple tree species utilization.
- Silvicultural goals and objectives need not be significantly altered in merchantable stands when topographical or ground conditions have less than 15% slope and are relatively smooth.
- The increased value of fiber recovered from whole tree operations may create profitable harvesting conditions in stands now considered marginal or submarginal.
- A mechanized logging system is essential in stands with merchantable stand diameter of less than 25-cm d.b.h. or in stands where little or no log-quality material is produced. Mechanized equipment includes a feller/buncher, grapple or cable skidder, and mobile chipper.
- Cost to fell, skid, and chip has averaged $11/tonne not including trucking costs.

The economics and net energy efficiency of harvesting and transporting energy wood are being studied at Alabama A&M. To determine the influence of the cycle elements on cycle time, standard time study techniques were used. Individual cycle elements, delays, and total cycle time were recorded for each observed turn, using techniques developed by the American Pulpwood Association. Data developed are used in comparing economics, fuel consumption, productivity, and environmental effects of cable yarder systems versus conventional skidding systems, and cable systems are studied on a range of terrain conditions.

Two cable yarder operations were analyzed individually to determine the effects of the various cycle elements on its production. A total of 58 observations of a custom-built yarder were timed over 4 days of observation. Table 2-5 summarizes the elemental cycle times and shows the contribution to total cycle time. Hook time accounted for 23% of the cycle time. Delay time was the second largest factor, accounting for 21% of the total cycle time.

The Christy yarder was also studied for 4 days. Table 2-6 summarizes the cycle element times. Lateral out was the largest single cycle element, accounting for 25% of total turn time.

Table 2-5.
Custom-built yarder
Summary of times for each cycle element (minutes)

Element	Total	Mean	Standard Deviation	Range	% of Total Turn Time
Outhaul	38.02	0.66	0.10	0.40-1.20	7
Lateral Out	87.29	1.50	0.16	0.10-3.60	16
Hook	130.39	2.24	0.19	0.30-5.30	23
Lateral In	48.45	0.84	0.12	0.10-3.10	9
Inhaul	91.08	1.57	0.16	0.30-2.60	16
Unhook	48.44	0.83	0.12	0.10-2.10	9
Delay	115.48	1.99	0.18	0.10-42.82	21
Total Turn Time	559.15	9.63	1.03	1.4-60.72	101.0[a]

[a] Percentages do not total 100 due to rounding.

Table 2-6.
Christy yarder
Summary of times for each cycle element (minutes)

Element	Total	Mean	Standard Deviation	Range	% of Total Turn Time
Outhaul	14.66	0.32	0.09	0.17-0.50	7
Lateral Out	54.41	1.18	0.76	0.35-5.05	25
Hook	34.42	0.75	0.62	0.16-3.02	16
Lateral In	27.22	0.59	0.39	0.23-1.93	12
Inhaul	32.16	0.70	0.47	0.22-3.00	15
Unhook	18.69	0.41	0.17	0.20-1.13	9
Delay	33.72	0.73	1.52	0.00-5.32	16
Total Turn Time	215.58	4.68	2.02	1.98-10.69	100

D. HERBACEOUS CROPS

The Herbaceous Crops Program is a cooperative effort between the U.S. Department of Agriculture and the Biomass Energy Technology Division. The research emphasis is on vegetable oil as fuel for compression ignition engines; plant sources for energy and chemicals; and production of plants for biomass and chemicals under conditions of salinity, water stress, and nutrient stress. A variety of selected derivatives from among soybean, peanut, sunflower, and rapeseed are being evaluated as fuels in diesel engines. Fuels are being formulated to improve combustion. For selected species, such as napier grass grown in southeast Florida, a productivity goal of 28.6 dry tonnes/ha-yr is envisioned. It has been estimated that 50 million hectares of marginal land could be made available for production of herbaceous crops. Three feedstock types are being considered: grasses for direct conversion to energy (e.g., napier grass), plants grown for oils (e.g., Chinese tallow), and plants grown for their hydrocarbon content (e.g., milkweed). This research involves species screening and small field plot experiments. Selected species from these experiments are tested to assess their performance using various crop production strategies.

Literature is being surveyed for promising energy crops, including plant biomass, seed oils, and hydrocarbon and whole-plant oil. The availability of sawmill and logging residues also is being determined. Plant species are being collected in arid/semi-arid western states and subsequently evaluated as sources of high-energy extractable constituents, such as hydrocarbons and whole-plant oils.

1. Liquid Engine Fuels

The potential of vegetable oil as an alternate source of liquid fuel for agriculture in the Pacific Northwest is being studied by the University of Idaho. The objective is to evaluate the potential of three oilseeds adapted to the Pacific Northwest as a source of liquid fuel for diesel engines. The yield required per hectare to enable competition with diesel fuel depends on a number of economic, region-specific factors, such as the cost of the land. For example, in the Pacific Northwest, it is envisioned that a yield of 1860 L/ha-yr from large-scale plantations would be needed to achieve cost competitiveness. Cost-competitiveness can also be affected by refining costs and engine modifications that may be necessary to use various vegetable oils as a diesel substitute.

The average oil yields for six cultivars of winter rape ranged from 1050 to 1940 L/ha when grown in northern Idaho. In the Pacific Northwest, yields ranged from 867 to 1740 L/ha. Some cultivars averaged about 33% more oil per hectare than the others. Since some are high in erucic acid and some are high in oleic acid, it is possible to have high yields with widely differing fatty acid content.

The oil production potential for safflower is much lower than for winter rape in both Idaho and the Pacific Northwest. The variation in observed yield also indicates extreme sensitivity to environmental conditions. Sunflower also indicates lower oil production potential than winter rape in both Idaho and the Pacific Northwest. It also has a widely varying yield depending upon location.

Oleic sunflower (*Helianthus annus* L.), and linoleic safflower (*Carthamus tinctorius* L.), and low and high erucic acid rapeseed (*Brassica napus* L.) oils were evaluated for fatty acid composition, energy content, viscosity, and engine performance in short-term tests. During 20-minute engine tests, power output, fuel economy, and thermal efficiency were compared to diesel fuel (Table 2-7). Fatty acid composition of selected cultivars was evaluated to determine the range of variation available within and between the three crop species.

Vegetable oils contained 94% to 95% of the energy content (kJ/L) of diesel fuel (Table 2-8), but were 11.1 to 17.6 times more viscous. Viscosity of the vegetable oils is related to fatty acid chain length and number of unsaturated bonds (Fig. 2-11). During short-term engine tests, all vegetable oils produced power outputs equivalent to diesel's and had thermal efficiencies 1.8% to 2.8% higher than diesel's. The most within-species variation in seed fatty acid composition occurred in safflower (Table 2-9).

An off-the-shelf seed processing system was built that has proved to be a workable system readily adaptable to most farm operations in the Pacific Northwest. Initial investment costs are estimated at $10,000, and production costs per liter of oil range from $0.50 to $1.00. The economic balance of using the oil for fuel vs. selling it on the open market is unfavorable at current diesel fuel prices; however, if the availability of fossil fuels diminishes and if prices continue to rise, the economics may swing in favor of vegetable oil to power U.S. agriculture. It has also been suggested that if plants were established they could provide oil for existing oil markets with the option of switching the production to fuel use in time of emergency.

2. Power and Fuel Consumption Tests

During the maximum power and fuel consumption tests of the five vegetable oils, power output of the engines did not vary significantly for the different oil blends although there was a general tendency for power to increase 2% to 3% at the 50-50 blends. Fuel consumption by volume was the same as for diesel fuel and thus was higher for the vegetable oils on a weight basis. Thermal efficiency was also higher for the vegetable oil fuels. Differences in engine performance are so small that in actual operation an operator would not detect which fuels were in use. Data from the varying power tests are shown in Table 2-10.

Two single-cylinder, water-cooled, diesel engines with precombustion chambers and pintle type injectors were used for long-term tests. Four cycles—one with diesel fuel and one with linoleic safflower oil—and two with a 70% winter rape - 30% No. 1 diesel fuel blend with and without a dispersant additive—have been conducted.

The safflower oil was chosen for the first tests because of its low viscosity. The winter rape blend was chosen because the erucic acid has only one double bond, which reduces the oxidation and polymerization rates. No. 1 diesel fuel was added (30%) to the winter rape to reduce the viscosity to acceptable levels.

A three-cylinder tractor was also operated on 100% linoleic safflower oil for 150 hours over a 15-month period. The tractor was first operated on a 50-50 mixture of sunflower oil and diesel. In another test, the tractor's main tank was filled with 100% safflower oil, which was used as the principal fuel. The tractor was used for approximately 120 hours for general farm work and the remainder in short-term demonstrations in many areas of Idaho. Another tractor was used by the University of Idaho Plant Science farm in its spring and summer tillage work. Operator observations, cylinder compression, and power tests were performed every 50 hours to monitor tractor condition and performance.

Measurements and weights showed about twice the wear rate for the safflower-fueled engine compared to the diesel engine. The safflower-fueled engine also showed more carbon in the combustion chambers and additional varnish and carbon build-up on the injector nozzle.

Table 2-7.
Power output, fuel consumption, specific energy, and thermal efficiency of five vegetable oils and No. 2 diesel during short-term engine tests

Fuel Type	Power (kW)	Fuel Consumption (kg/h)	(L/h)	Specific Energy (kWh/L)	Thermal Efficiency (%)
Oleic Safflower	30.0	10.2	11.0	2.72a*	27.0a*
Linoleic Safflower	29.5	10.4	11.2	2.64ab	26.0b
Erucic Rape	29.4	10.0	10.9	2.69a	26.6ab
Oleic Rape	29.7	10.2	11.1	2.69a	26.5ab
Sunflower	29.5	10.1	10.9	2.70a	26.7ab
No. 2 Diesel	29.5	9.7	11.4	2.59b	24.2c

*Means within a column not followed by the same letter differ at the 0.05 level of probability according to Duncan's New Multiple Range Test.

Table 2-8.
Specific gravity, viscosity, and heat of combustion of five vegetable oils and No. 2 diesel

Oil Type	Specific Gravity (g/ml)	(ratio)[a]	Kinematic (mm^2/s)	Viscosity (ratio)[a]	Heat of Combustion (kJ)	(ratio)[a]
Sunflower	0.92	1.08	34.9d*	12.0	2081b*	0.95
Linoleic Safflower	0.93	1.09	32.3e	11.1	2082b	0.95
Oleic Safflower	0.92	1.09	42.1e	11.1	2064b	0.94
Oleic Rape	0.92	1.08	39.0c	13.4	2096b	0.95
Erucic Rape	0.91	1.07	51.0a	17.6	2086b	0.95
No. 2 Diesel	0.85	1.00	2.9f	1.00	2196a	1.00

[a]Relative to No. 2 diesel.

*Means within a column not followed by the same letter differ at the 0.05 level of probability according to Duncan's New Multiple Range Test.

Table 2-9.
Fatty acid composition of selected cultivars of three species of oilseed crops

Species Cultivar	Fatty Acid						
	Palmitic 16:0[a]	Stearic 18:0	Oleic 18:1	Linoleic 18:2	Linolenic 18:3	Eicosenoic 20:1	Erucic 22:1
	% by weight methyl esters[b]						
Sunflower							
Hybrid 894	6.2	4.2	17.8	71.6	—	—	—
Safflower							
S112	6.3	1.6	9.1	83.1	—	—	—
S208	6.0	1.8	9.0	83.2	—	—	—
S541	6.7	2.0	10.3	81.0	—	—	—
UC-1	4.4	1.2	71.7	22.7	—	—	—
Winter Rape							
Sipal	4.1	1.1	58.1	22.5	14.1	—	—
WW827	3.6	0.8	55.3	25.8	14.5	—	—
WW843	3.1	0.8	56.5	24.8	14.9	—	—
ORB 78-253	2.5	0.4	14.4	17.1	22.8	T	42.8
Norde	2.3	0.3	14.3	15.6	24.1	T	43.4
Dwarf Essex	2.9	0.7	13.7	15.3	12.9	6.4	47.5

[a]Number of carbons and unsaturated bonds, respectively, for each fatty acid.

[b]May not sum to 100% due to presence of other minor fatty acids. Clear separation of linolenic and eicosenoic fatty acids is not possible using this technique.

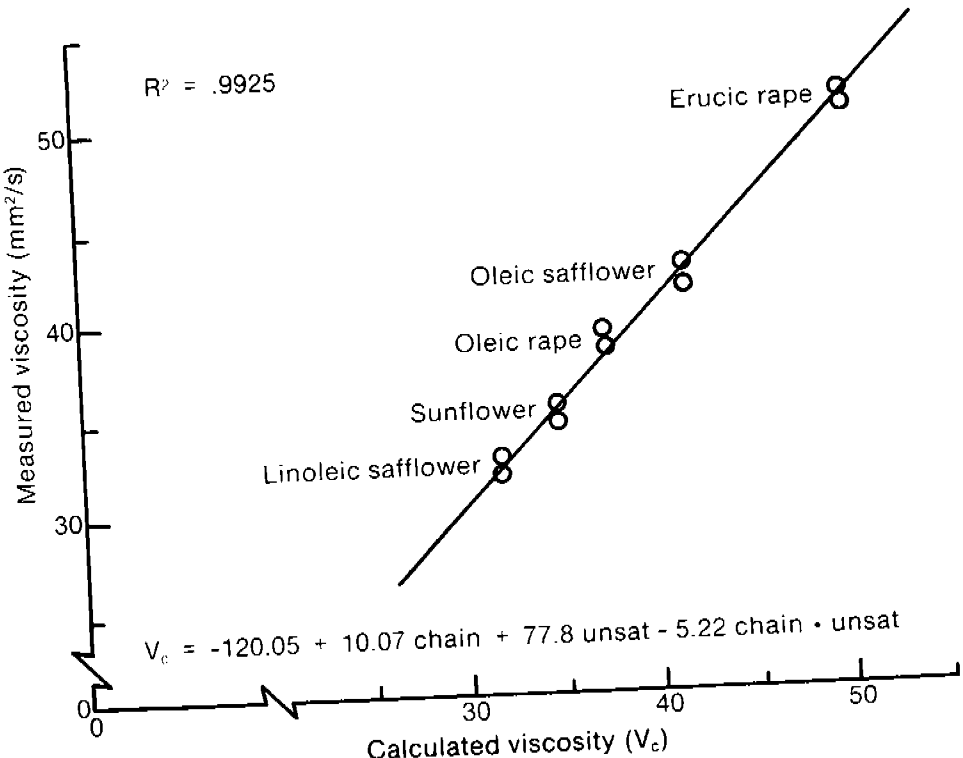

Fig. 2-11. Comparison of estimated viscosity with actual viscosity of five vegetable oils

Table 2-10.
Power, fuel consumption, and thermal efficiency measured in a varying load test with winter rape-diesel blends as fuel

Fuel Type	Power (kW)	Fuel Use (kg/h)	Thermal Efficiency (%)
100% Diesel			
100	27.8	9.4	26.8
75	21.0	6.8	27.8
50	13.9	5.1	24.8
25	7.1	3.6	17.7
0	1.3	2.5	7.6
25% Winter Rape			
100	29.8	10.1	25.7
75	22.3	7.1	27.6
50	15.2	5.2	25.3
25	7.5	3.8	17.3
0	1.2	2.7	3.9
50% Winter Rape			
100	29.7	10.1	24.8
75	22.3	7.1	26.6
50	15.0	5.3	23.7
25	7.5	3.8	16.7
0	1.0	2.7	3.0
75% Winter Rape			
100	29.1	10.2	23.3
75	22.0	7.1	25.5
50	14.6	5.2	23.0
25	7.4	3.7	16.3
0	1.1	2.5	3.7
100% Winter Rape			
100	28.3	9.6	23.5
75	21.0	6.9	24.3
50	14.2	5.2	21.7
25	7.1	3.7	15.3
0	0.9	2.8	2.6

Engine used was a 2.8-L direct injection, 4-cylinder diesel with hole-type injectors manufactured by Ford.

For the test durations indicated and for the particular engine used, the winter rape blend is superior to the linoleic safflower as a fuel. In all cases where the safflower oil was used, the engines suffered severe degradation—primarily a result of ring gumming, lubrication oil thickening, and some injector gumming. None of these problems was found in the engine fueled with winter rape oil. Some gumming was noted on the upper piston land although it had not progressed to a point where engine performance was affected.

The oil analysis also indicated excessive oxidation, high iron, aluminum, chromium, silver, molybdenum, tin, and lead for the engine operated on linoleic safflower. The engine fueled with winter rape blend was equivalent to diesel in nearly all of these factors. No engine maintenance problems would have been detected by the oil analysis data during the long-term endurance cycle using winter rape as a fuel.

3. Energy and Chemical Substitutes

Scientists at the U.S. Meat Animal Research Center are looking into anaerobic fermentation of beef-cattle manure and crop residues. The objective is to develop optimum design criteria for a two-stage fermentation system that allows rapid conversion of easily degraded compounds to methane and long-term fermentation for more slowly degraded compounds.

A two-stage fermentation system was developed with and without solids separation, which converts manure-straw mixtures to methane. The pilot-scale findings showed that the system with solids separation produced only 58% of the daily methane production of the system without solids separation. However, the added energy cost of grinding wheat straw before mixing it with beef-cattle manure makes the without-solids-separation fermentation process less attractive.

Advantages of fermenting manure and crop residue mixtures are the increased amount of substrate (crop residue in addition to manures) available for fermentation, the general availability of crop residue where livestock are raised, and the nutritional compatibility of the highly nitrogenous manure and highly carbonaceous but nitrogen-deficient crop residue. Major problems associated with fermenting crop residue are the low biodegradability of untreated crop residue, the high cost of pretreating the residue, loss of readily available substrate during pretreatment, the production of inhibitory substances when crop residue undergoes severe thermochemical treatment, and the physical properties of crop residue that make it difficult to pump and mix these slurries.

The advantages of the proposed two-stage fermentation system are thermochemical pretreatment or size reduction of the crop residue is not required, the crop residue is handled only at the beginning and end of fermentation (i.e., materials handling problems associated with mixing and pumping crop residue slurries are minimized), and the system will selectively ferment the easily and less degradable compounds. Optimum design criteria for the system will be determined through a parametric testing program, and an economic assessment will be performed on the optimized system.

4. Corn Drying

Corn drying using heat from a direct-fired crop residue furnace is being studied at Iowa State University. The objective is to investigate the technical feasibility of drying corn in a continuous-flow dryer using direct-fired heat from a concentric-vortex, direct-combustion, crop-residue furnace.

Eleven field tests were conducted with the dryer-furnace system set up at the Agronomy-Agricultural Engineering Research Center, west of Ames, Iowa. Five different biomass fuels were used. Data taken included system temperatures, fuel feed rate, furnace and dryer air-flow rates, corn mass, and mass loss. Figure 2-12 shows the field test apparatus.

Table 2-11 shows fuel and furnace results for the field tests. Furnace efficiency is the ratio of net energy out to net energy in. By fuel, it ranged from 25% to 92%. Tree leaves burned poorly in these tests; corn cobs worked best.

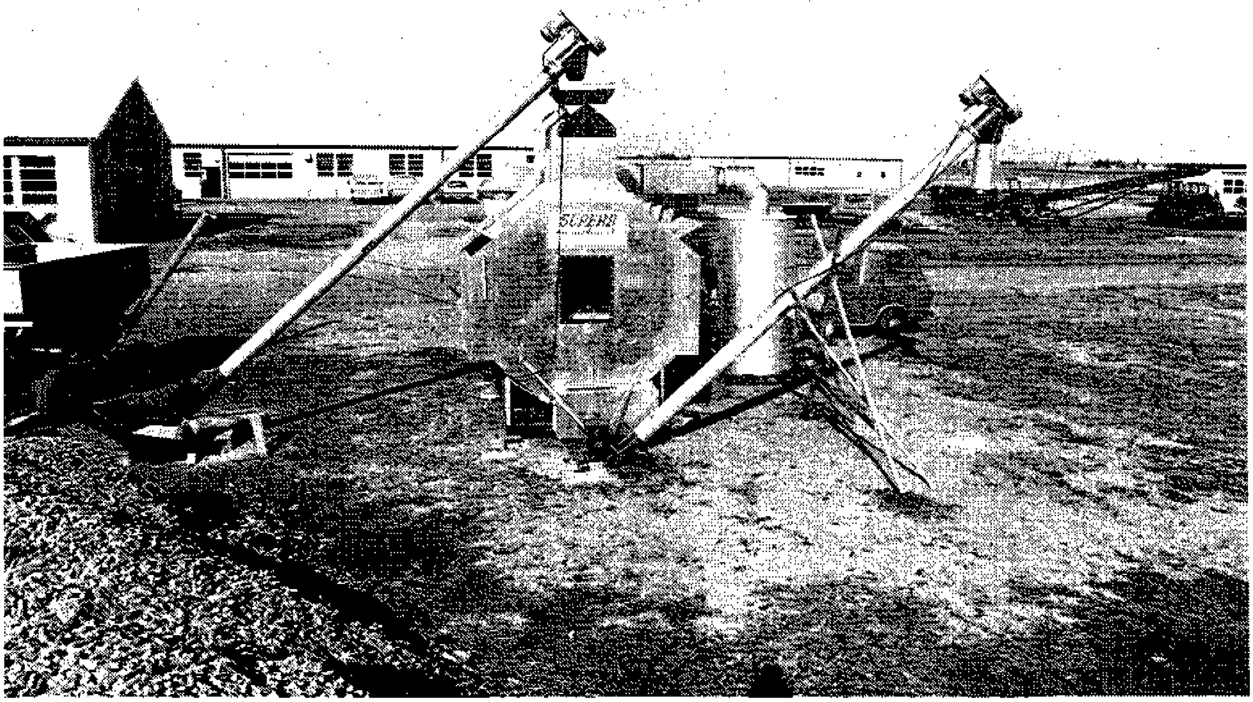

Fig. 2-12. Biomass corn drying experimental apparatus at Iowa State University

Table 2-11.
Fall 1981 biomass corn drying furnace efficiency

Fuel				Furnace		
Type	No. of Samples	Feedrate (kg/h)	MCWB (%)	Net Energy In (MJ/h)	Net Energy Out (MJ/h)	Efficiency (%)
Tree leaves	1	73	41.2	532	134	25
Corn cobs	5	77	22.3	1004	923	92
Corn stover	2	57	12.4	853	623	73
Soybean straw	2	111	21.2	1463	729	50
Wood shavings	1	73	39.7	725	623	86

MCWB - moisture content (wet basis)

Samples of dried corn were taken at the completion of drying. Quality indicators in use included USDA grading and chemical analysis for residue. Table 2-12 shows results of an official USDA grading procedure. Samples from six of the tests were graded sample grade because of commercially objectionable foreign odor. Corn, dried using cobs as fuel, seems to have the least odor problem.

Table 2-12.
Quality of corn dried in direct-fired crop residue furnace

Fuel Type	Corn MCWB, % Initial	Corn MCWB, % Final	Drying Temperature, °C Average	USDA Grain Grade
Tree leaves	27.1	14.1	22	Sample—odor
Corn cobs	27.7	18.5	71	4—MC
Corn cobs	26.3	17.5	80	2
Corn cobs	25.3	14.0	50	Sample—odor
Corn cobs	25.1	16.1	45	3—MC
Corn cobs	22.8	16.1	65	3—MC
Corn stover	26.8	20.5	38	Lost
Corn stover	22.6	18.5	43	2
Corn stover	23.5	16.6	49	Sample—odor
Soybean straw	22.0	15.3	53	Sample—odor
Soybean straw	22.1	13.4	43	Sample—odor
Wood shavings	21.6	14.7	50	Sample—odor

MC - moisture content

MCWB - moisture content (wet basis)

5. Alternative Fuel Systems

At the University of Maine, scientists are developing an integrated system for the use of particulate wood and other biomass fuels for space and process heat. The objective is to develop a system for procurement, processing, delivery, and use of particulate biomass fuels for residential, commercial, and institutional space heating in rural areas of the Northeast.

Two furnace control systems using flame detection were developed. One type was tested on five residential wood chip furnaces during the 1981-82 heating season. An intermittent ignition oil burner primary control was used as the basis for this system with two overriding time delay relays—one to allow accumulation of chips in the firebox before ignition was attempted and the second to extend and control the ignition period. All units worked well with little servicing needed other than periodic inspection of the flame sensors to ensure that they were not obscured by soot or fly ash.

A very small chip burner with only 77 cm^2 of grate area was used to fire a small boiler plumbed as a side arm on an electric water heater during the summer of 1982. The unit burned 1.8 kg of chips/h while firing and was arranged to maintain a standby fire on 0.34 kg of chips/h. The thermal capacity of the water in the 197-L electric water heater to which the chip unit was attached was used to absorb the heat generated during standby periods. The temperature of the stored water rose from 60° C to more than 100° C during some nights, indicating that a larger storage was desirable.

It seems that units of this size (about 26,000 kJ/h) should be further developed since many residences now being constructed in the area have design heating loads as low as 26,000 kJ/h. Only $300 in materials were used in the prototype burner and boiler, indicating that a very economical small residential unit could be made.

Approximately 40,000 hours of operating time were logged by the 25 wood chip burners being monitored in Maine during 1981-82. All automatic safety systems operated as designed. Furnace reliability is now extremely good; for example, one unit ran without attention for 2 weeks in April 1982 while another had no unscheduled shutdowns for a 184-day period from January to July 1982.

Convection drying of a 1.5-m depth of chips in a storage bin reduced moisture content from 41.5% to 22% (wet basis) over a 2-month period with only slight molding and heating. Continuous ventilation of a similar depth of chips at 7.6 $m^3/min\text{-}m^2$ in September 1982 dried the entire bin to 18% moisture content in 7 days. Ventilation of a 6350-kg batch of chips loaded to a 1.5-m depth with 2.1 $m^3/min\text{-}m^2$ of solar-tempered air reduced overall moisture content from 40% to 11% in 24 days of continuous operation.

Any size particle from sawdust to chips 13 cm long can be handled and burned in the equipment being tested without blockages occurring. However, 15-cm-long chips tend to lodge in the 13-cm and 15-cm pipes being used as fuel feed tubes to the fireboxes. Sawdust particles tend to burn before they reach the mass of burning chips on the grate and carry over into the heat exchanger as fly ash. A maximum of 10% sawdust is recommended.

Chips at 40% to 45% moisture content (wet basis) (i.e., green hardwood chips) are being burned successfully in approximately 70% of the furnaces being monitored. However, chips of this moisture content cannot be stored for many days, unless they are frozen, because biological fermentation and heating occur. When frozen, the chips adhere to walls and to each other, making mechanical feeding difficult. Chips dried to 30%

moisture content do not adhere when frozen and can be fed mechanically. Moisture contents of 20% or less are desirable for reliable, fast ignition by the electric igniter guns now being tested. Oil burner ignition or use of a timer to maintain a standby fire is recommended for installations using green or only partially air-dried chips. Green softwood chips are 50% to 55% moisture content (wet basis) and do not burn well in small furnaces under any circumstances.

Researchers at Arizona State University are studying the catalytic conversion of biomass-derived synthesis gas to diesel fuel in a slurry reactor. The objective is to develop a slurry-phase, chemical-reaction system to convert synthesis gas representative of that obtainable from biomass gasification to diesel fuel that can be used directly in existing engine designs.

During the first year of the project, the experimental system was completed (Fig. 2-13), and the experimental program started. A limited amount of mathematical characterization of the system was performed as was a comparison with fluidized bed performance.

The current best slurry combination is unsupported cobalt oxide (without calcination) in Fischer paraffin oil, with product yields of about 69 L of diesel-type fuel per tonne of biomass feed (for typical pyrolysis system performance). Current efforts are aimed at adjusting the base point conditions to improve the product yields via improvements in the gas-liquid-solid contact time. This involves improvements in gas distributor plate design, adjustments in gas flow rates, and characterization of the solubility and diffusion rates of the gas components in the liquid media. When gas point yields of about 137 L/tonne are achieved, a factor study will be performed to establish the effect of temperature, pressure, and feed gas composition (ethylene, hydrogen, carbon monoxide) on the product yields and quality.

The Northern Agricultural Energy Center, USDA, Agricultural Research Service (ARS), is studying physical and chemical modification of vegetable oils and physical/chemical properties of the modified oils that are related to combustion in a diesel engine. The transesterification reaction is being investigated with several different alcohols and vegetable oils as a means of improving the viscosity and volatility of fatty acids present in the vegetable oils and, hence, of improving combustion properties.

The ester content of methyl, ethyl, and butyl esters from transesterified sunflower oil was strongly influenced by the molar ratio of alcohol/vegetable oil, the type of catalyst (basic or acidic), and reaction temperature. At a 6:1 molar ratio of alcohol/sunflower oil, 0.5% sodium methoxide catalyst, and reaction temperatures near the boiling points of the alcohols, the weight percent of the three esters ranged from 96 to 98 after 1 hour. At the stoichiometric ratio of 3:1, the range decreased to from 81% to 88% and continued to decrease at lower ratios. Transesterification with acid catalysis was much slower than with basic catalysis. With 1% sulfuric acid and a 30:1 molar ratio of alcohol/soybean oil, the methyl, ethyl, and butyl esters required 69, 21, and 3 hours, respectively, to be formed at ca. 94% when the reactions were conducted near the various boiling points of the alcohols (65°-117°C). When all three alcohols were allowed to react at 65°C for 45 hours, the weight percent of the esters ranged from 73% to 87%. At moderate temperatures (32°C), vegetable oils can be 99% transesterified in about 4 hours with alkaline catalyst.

Refined soybean, sunflower, peanut, and cottonseed oils responded about the same to decreasing molar ratios of methanol/vegetable oil. At a 6:1 molar ratio, ester content ranged from 93% to 98%; that decreased to from 74% to 84% at a 3:1 molar ratio. Crude oils were also transesterified at a 6:1 molar ratio. The percent ester yields (and percent

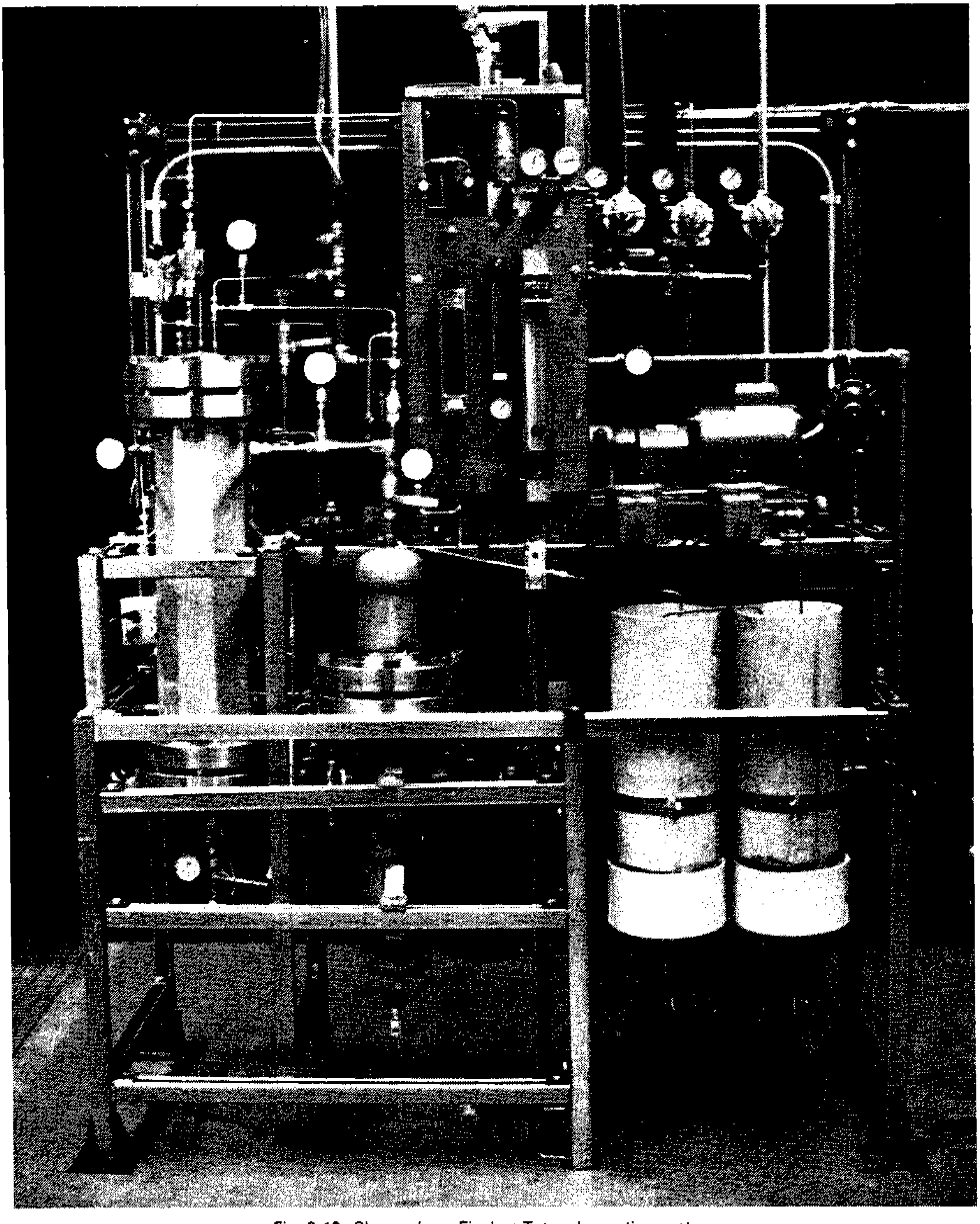

Fig. 2-13. Slurry-phase Fischer-Tropsch reaction system

purity) from crude cottonseed, soybean, sunflower, and peanut oils were 86(98), 86(96), 85(95), and 69(96), respectively. The reduced yields from the crude oils compared to the refined oils are due to gums and other extraneous material present in the crude oils. The recovery of glycerol formed during the transesterification of refined sunflower, peanut, and cottonseed oils was also determined. Glycerol yields were about the same for all three oils and depended upon the molar ratio of alcohol/oil used. With sunflower, for example, the molar ratios and resulting yields of glycerol were 6:1, 100%; 5:1, 100%, 4:1, 79%; 3:1, 60%; 2:1, 17%; 1:1, 0%.

North Dakota State University is evaluating sunflower oil as diesel fuel in direct-injection engines for cylinder wear and other effects following the Equipment Manufacturers' Association's proposed 200-hour preliminary durability screening test. Fuels include vegetable oils blended with diesel fuel, methyl esters, and hybrid fuels containing vegetable oils and wet alcohol.

A blend of sunflower oil/No. 2 diesel fuel (25/75) caused erratic injector nozzle performance during the initial 60 hours. Nozzles were changed; however, the problem recurred by the end of the test. These observations signify failure of the stringent test criteria. Examination of the engine parts revealed abnormal carbon buildup on injectors, heavy carbon deposits above ring travel, and worn rod bearings. Barium-based smoke suppressants and ashless dispersant fuel additives were evaluated during abbreviated tests with the 25/75 fuel blend. The former was not beneficial; however, the latter merits further study. A hybrid fuel formulation containing more than 50% vegetable oil showed some positive results; however, the fuel did not pass the screening test. Significant crankcase dilution and abrupt viscosity increase necessitated oil changes at 60-hour intervals.

The Economic Botany Laboratory, ARS, is preparing information summaries on 200 of the most promising biomass fuel species, including any (up to 200) recommended by the sponsors during the first year of the project. Information summaries will contain precise paragraphs, documented by recent references where available, on the nomenclature, uses, folk medicine, chemistry and nutrition, morphology, germplasm, distribution, ecology, cultivation, harvesting, biotic factors, yields and economics, bibliography, and energy potential of each species.

The University of Georgia, in a 2-year project, is determining the physical characteristics, quantity, price, and current market distribution of biomass fuel supplies from sawmill and logging residues in Georgia and the Southeast. The forest products industries in Georgia and surrounding areas are being surveyed for information on wood residue: type, sources, quantities, availability, handling, hauling distances, and costs. Data obtained by a questionnaire prepared by the University of Georgia, Athens, are being stored for further processing during the second year of the study. A linear program model will be developed to determine a least-cost fuel mix for specific users. Heat and moisture contents of the variety of residues will be determined and factored into the model.

6. Plant Production Under Stress

Plant taxonomists in a 3-year program are collecting plants in a systematic study to identify promising biomass/botanochemical species from the arid/semiarid western states. The plant scientists with Plant Resources Institute, Salt Lake City, Utah, provide a historical record and prepare voucher samples for reference; and chemists evaluate the plants for content of botanochemicals. To provide for a uniform basis for comparison and to be consistent with the basic program of the Northern Agricultural Energy Center, ARS, plants are collected at fruiting stage.

Texas A&M University and Texas Tech, in a 3-year study, are evaluating unconventional plant species for the production of biomass in semiarid environments with minimum inputs of water and fertilizer (low production costs). The overall objective is to identify genotypes selected from three unconventional species, Atriplex canescens (salt bush), Kochia scoparia, and Sorghum halepense that possess exceptional biomass productivity based on drought and salinity tolerance. Seed collections from other researchers and government agencies and their own from the southwest United States will be made. Seeds of each species will be sown in large beds under conditions previously determined for each species. Saltbush seeds will be dewinged, treated to remove germination inhibitors, and planted at 1 cm depth. Germination varies greatly with seed source and seldom exceeds 50%. Selection of those individuals that exhibit exceptional seedling vigor and thus potential biomass production is being made. Growth is being monitored by measuring stem length, number of leaves, and leaf area.

An Illinois State University research project was part of a larger program to demonstrate the feasibility of using grass species to produce plant biomass for energy conversion on strip mine spoils. Grass species tested included native prairie grasses and domestic forage species. The grasses were planted on strip mine spoils with and without soil amendment through application of municipal sewage sludge. The use of strip mine spoils to produce biomass for energy conversion will retain prime agricultural land for crop production. The grass cover should reduce soil erosion and enhance soil improvement on strip mine spoils. The prairie grasses used for biomass production are all warm season C-4 plants that make their maximum growth during July and August. Cool season domestic grasses (C-3 plants) were also established. A summary of significant observations is:

- There were no differences in seedling establishment attributable to time of planting or type of grass planted.
- Significantly more seedlings were established on unamended plots than on sludge-amended plots.
- Total annual biomass production (weeds and planted grasses) was not significantly affected by time of planting.
- Examination of biomass production by month revealed that there were significant differences in production between spring and fall plantings for June, July, August, and September. Fall-planted plots produced more biomass in June and July than did spring-planted plots; the reverse was true for August and September.
- Amended plots produced significantly more biomass than did unamended plots.
- For biomass samples taken in September, the ranking of the plantings in terms of aboveground production for the planted grasses was as follows: (1) fescue, (2) reed canary, (3) mix of three prairie grasses, (4) switchgrass, (5) little bluestem, and (6) Indian grass.

E. AQUATIC SPECIES

The Aquatic Species Program addresses the use of plant biomass that occurs naturally in wetland or submerged areas. Processes are being developed to capitalize on the inherent capacity for rapid growth as well as on the extraordinary chemical composition of aquatic plants. Emphasis is placed on salt-tolerant species for cultivation on poorly utilized, low-value lands, where conventional agriculture is not economical. Candidate species include microalgae—unicellular plants that are natural factories for converting sunlight into high quality oils; macroalgae—large, chemically unique plants that can be easily fermented to methane gas or alcohols; and emergents—plants that grow rooted in waterways and bogs, but are partially exposed above water. All four types of aquatic plants are capable of rapid growth and can provide biomass yields that surpass those of land plants. For example, extrapolating from laboratory results, it has been estimated that microalgal lipid oil productivity could be as high as 36 barrels of oil equivalent/ha-yr. The program completion point is defined as the date by which economic/technical feasibility has been demonstrated to industry in a manner conducive to encouraging commercialization. Market price forecasts for this date then become the program cost goal for lipid oil. Given that the program goal is to achieve commercial feasibility by 1998, the mid-price scenario for that date, $100/barrel of oil equivalent, is chosen as the program element cost goal.

Research and development activities in the Aquatic Species Program are conducted in four mutually dependent areas: species selection, cultivation requirements, processing technology, and systems integration. Species selection involves the collection, identification, and characterization of plants classified in each category under the program's purview. Selections are made comparing growth rates, light requirements (both intensity and wavelength responses), temperature tolerance, nutrient demands, salinity and pH limitations, and chemical compositions. Cultivation requirements are often established empirically through effects-of-variables studies. Processing technology involves the harvesting, fractionation, and conversion of aquatic plants into fuels or other energy products. Systems integration provides the definition of components required for fully functional, practical systems.

Microalgal research is emphasizing the selection and characterization of microalgae available from sites in the deserts of the southwestern United States. Investigations were performed to identify the regulation and control mechanisms that affect the biosynthesis of lipids in such microalgae and to provide clues for developing the ability to manipulate the chemistry of microalgae produced outdoors. Work was done to establish the parameters affecting sustained high yields from experimental outdoor systems. These data are used to improve the design and cost benefit of such systems. Resources such as saline water, insolation, nutrient supply, climate, and CO_2 availability are being surveyed to identify potential sites and site-related problems of microalgal production within the southwestern deserts.

Microalgal research is directed toward developing efficient land-based operations for production and processing systems. Performance comparisons were made between two promising seaweeds, Ulva and Gracilaria, on their respective abilities to tolerate fluctuations in pH, carbon availability, volume exchange rates, temperature, and salinity. Sustained productivity limits were established, and economic factors such as capital investment, operating costs, and projected revenues associated with such systems were examined.

Efforts will continue to define and develop technologies appropriate for emergent plant systems. Research focuses on establishing practical procedures for planting, managing, and harvesting cattails in Minnesota wetlands.

1. Microalgae

Sustained yield performance of shallow algal culture is being studied by the University of Hawaii. A series of two-level factorial experiments in four 8.2-m^2 raceways was used to determine the relative importance of operational parameters. Photosynthetic efficiency and yield will be maximized using second-order factorial design experiments in five 8.2-m^2 raceways.

Previous work has led to the selection of the marine diatom Phaeodactylum tricornutum since it tolerates a wide range of pH, salinity, and temperature; tends to dominate outdoor mass culture; can withstand buffeting; and excretes products that appear to be inhibitory to the growth of both bacteria and other algae. Most important, the lipid content of P. tricornutum is anomalously high among algae, reaching 80% of its dry weight under appropriate growth conditions.

FY 1982's work encompassed three primary experimental devices: a 50-m^2 flume, foil inserts, and five 8.2-m^2 flumes. Almost all research was performed in the 50-m^2 flume. Initially, cell densities peaked around 10^7/ml; but with the addition of CO_2 to the medium, cell densities in excess of 2 x 10^7/ml were realized. At this point, a monad predator began to appear and rapidly grazed down the population. In response to this problem, several mechanisms of predator control were developed, including sonicating, sedimentation, chemical addition, and pH increase from 8 to 9.0-9.5. By using pH control and sedimentation, researchers reported cell densities consistently more than 2 x 10^7/ml in the flume, and the flume culture has been maintained continuously for 7 months. The highest flume cell density to date has been 4.6 x 10^7/ml. Production during the last 3 months of the study averaged more than 11 g/m^2-d during a 30-day continuous operation experiment in a mass culture of P. tricornutum (see Table 2-13). This level of productivity in an outdoor system is approximately one-fourth the cell density achieved in the laboratory. Extrapolating the lab results, microalgal productivity of up to 66 dry tonnes/ha-yr is possible.

During the year, the idea of using foils to effect systematic vertical mixing in the flume was developed. The optimum angle of attack on the foil was found to be approximately 23° at the flow rate and culture depth of the system, with the foil arrays being placed 1.2 m apart (see Fig. 2-14). The flume was run for a week with the foil arrays in place and for an additional week with the foil arrays removed. The results of these two 1-week studies are summarized in Table 2-14. In terms of cost, the foils are simple to fabricate from molds, involve no moving parts, and create negligible pressure drop through the system.

Construction has been completed at the University of Hawaii on five 8.2-m^2 flumes. These raceways allow the use of factorially designed experiments capable of relatively quick evaluation of a complicated array of system variables including culture depth, cell concentration, flow rate, temperature, light quality (blue light versus ordinary sunlight), pH, salinity, and nitrogen source. Based on results of foil insert testing in the 50-m^2 raceway, foil design has been optimized; and the foil arrays to be used in the 8.2-m^2 raceways have been constructed.

A multiyear effort is planned by Georgia Institute of Technology, School of Applied Biology, to develop chemical profiles of microalgae. Microalgae will be collected and stable cultures grown and standardized. Baseline data to include general physical, chemical, and biological properties, will be established for each species. The effect of environmental parameters on these data will be measured. Pathways, control points, and regulatory mechanisms for the biosynthesis of lipids will be determined, and analytical procedures will be standardized. The types and quantities of lipids will be determined, and potential process techniques for lipid extraction will be investigated.

Four different algal species have been cultivated and extracted for total lipids, bound lipids, and carbohydrates. Lipid characterization of the desert algae Dunaliella and Isochrysis species has been initiated. To date, the cell accumulation studies have shown that the desert algae strains of D. bardawil, D. salina, and Isochrysis galbara, cultivated in an artificial hypersaline medium under controlled conditions, can achieve a doubling

Table 2-13.
Record of *P. tricornutum* production in 50-m^2 flume during the period from November 1981 to April 1982

Month	Production $g(dw)/m^2$-d	Light Intensity E/m^2-d	Efficiency %
Nov.	3.0	23.6	1.5
Dec.	2.4	22.5	1.3
Jan.	4.6	30.7	1.8
Feb.	10.5	37.0	3.4
Mar.	11.6	33.6	4.2
Apr.	11.3	40.2	3.4

Table 2-14.
Results of comparative 1-week productivity studies with and without foil arrays

	With Foils	Without Foils
Average Production (g[dw]/m^2-d)	5.35	2.57
Incident Light (E/m^2-d)	40.6	42.9
Photosynthesis Conversion Efficiency (%)	3.3	1.5

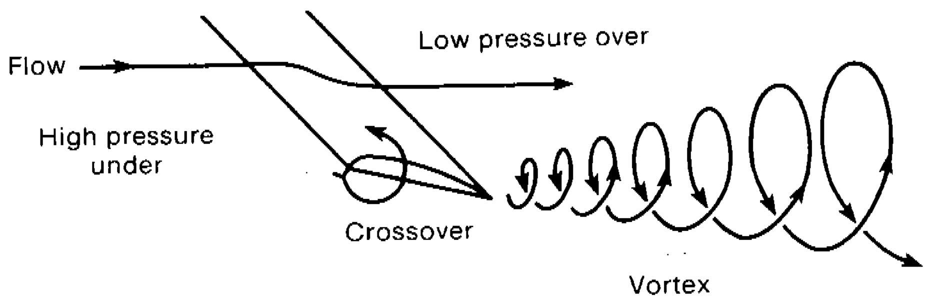

Fig. 2-14. Design of foil for systematic vertical mixing in flume

time of approximately 20 hours to maximal cell concentration of 2 x 10^7/ml. This indicates a reasonable doubling time with an excellent high culture density.

Enbio, Inc., is experimenting with the production of liquid fuels and chemicals by microalgae. A number of microalgal species were inoculated into the ponds to determine which species offer potential for high lipid yield. Additional data analysis will be performed on the physical, chemical, and biological responses of the algal species to system operational parameters. Laboratory studies of gross protein lipid and carbohydrate lipid will be conducted to determine the species exhibiting high lipid yields. A species will be recommended to the Solar Energy Research Institute for use in further pilot-scale experimentation studies during the next growing season.

Collection and selection of oil-producing desert microalgae were undertaken by the University of California, Institute of Marine Resources, Scripps Institute of Oceanography. The work consists of field isolations of microalgae that grow in saline desert environments—lakes, pools, and springs. These saline waters are analyzed for their inorganic chemical constituents so that proper media can be prepared for growing the desert algae. The desert algae will be assessed with regard to their maximum yields and efficiencies of light utilization and their proximate chemical composition. These investigations will provide significant basic data that can be applied to the possible outdoor culture of desert and marine microalgae as a source of energy.

A report, Algae from the Arid Southwestern United States: An Annotated Bibliography, lists and cross references by topical area past research literature on desert algae. The field trip into Northern California and Nevada to begin collection of desert algae has been highly successful in the sampling of alkaline lakes in the region. Seven sites and seven samples with salinity ranges from 4 to 160 ppt were collected from lakes in the Saline Valley, the Columbus Salt Marsh, and from lakes in the Mohave Desert. The field trip resulted in 60 batch cultures, 8 chemostat samples, 20 to 30 single cell isolates, and 24 to 36 agar plate cultures. In addition, contact with the Sierra/Nevada Aquatic Research Laboratory (U. of California, Santa Barbara) and the Fort Soda Mohave Desert Study Center (California State Colleges) will allow for support and coordination in future field trips into these regions.

Battelle Columbus Labs is identifying resources for aquatic biomass production in the Southwest. The environmental conditions suitable for microalgal production are examined, and the conditions for developing a matrix of physical and chemical requirements pertaining to the conditions existing in the U. S. southwestern deserts are quantified.

SERI has undertaken a cost analysis of microalgal production facilities. Efforts are directed toward developing cost histories of existing commercial microalgal facilities to determine capital equipment and operation cost requirements associated with the various design options. Financial models will be developed and used to assess overall economic feasibility, allowing identification of major cost drivers in production and potential economies of scale. Also, byproduct or coproduct economics and their impact on the production process will be identified.

A consultant agreement was established to provide cost histories of existing microalgal production facilities. These data are used to compile a capital and operational cost data bank for use in the financial analysis. An annual cash flow model was developed relating system physical outputs to financial cost estimates in order to calculate annual after-tax cash flow, rate of return, and a product price. A coproduct pricing model was developed to allocate the facility's fixed and operational costs to individual products. It was found that of a number of system technical and financial parameters, system yield and system capital cost had the greatest effect on overall system economics.

Jaycor is studying biological and engineering parameters of algal mass culture. Alternative microalgal culture systems designs and operations are evaluated, key parameters compared, and recommendations developed for improving the cost-benefit relationships associated with new fuels and chemicals applications for such systems.

Battelle Pacific Northwest Laboratory is evaluating blue-green algae as a nitrogen fertilizer replacement using the following approach: acquire strains of nitrogen fixing blue-green algae and screen for growth and nitrogen yield; conduct field tests of promising algal strains by treating unfertilized plots of corn with algal inocula and monitoring growth performance; and summarize the results to determine the feasibility of using blue-green algae as a fertilizer replacement for commercial agriculture.

Tolypothrix tenuis and Anabaena BN-165 were selected for use in the field tests on the basis of laboratory performance. Algal populations in the inoculated test plots multiplied 500- to 2000-fold during July. Corn from the test plots was harvested in early October. Preliminary results indicate that plots that received only algae produced as much corn as plots that received the recommended dose of nitrogen fertilizer.

2. Algal Oils Research

Algal oils research and development by SERI tests candidate microalgae species to develop data on the chemical and physiological responses each strain exhibits under specific environmental conditions. These data are used to provide a characterization of each microalgal strain to allow future selection of promising microalgae species based on oil production capability and specific growth characteristics. Maintenance of inoculum cultures in the laboratory provides a resource base for continued research efforts.

An oil-producing microalgae culture collection center was established at SERI with 24 species from 11 genera of green microalgae deposited. Cataloging and documentation of the oil-producing capacity will make SERI a national algal resource center to facilitate future research. Efforts have continued to collect, identify, and isolate salt-tolerant, oil-producing microalgae to augment the culture collection. One new strain, tentatively designated CX-S03, was isolated from a local soil sample. This oleaginous microalgae exhibits fast growth characteristics and is tolerant to 0.1 M salt. Specific growth responses of Chlorella sola also have been characterized. These tests indicate the important environmental adaptability of certain oil-producing microalgae to salinity stress. Physiological responses of Chlorella to nitrogen starvation and high salinity provide better insight into the mechanisms involved in the regulation of lipid formation and metabolism.

A microalgal systems simulation by SERI consists of the following steps: (1) obtain biological, physical, and engineering relationships to describe growth, harvesting, and processing and conversion of algae to final products, including energy and material requirements; (2) develop a process simulation model with built-in flexibility to describe the operations of alternative cultivation facilities (e.g., ponds or raceways, alternative harvesting techniques, filtration, flotation, centrifuging, and processes for production of alternative energy products); and (3) operate the model and supply results to be synthesized with production costs, operating costs, and other supporting data to screen alternative system concepts and identify the most promising R&D opportunities for system improvement.

The simulation model is being developed in two stages: production (or cultivation) and harvesting of algae, and processing and conversion to final products. The production and harvesting model has been completed, programmed, and checked out using an initial input data set derived primarily from laboratory experiments at the University of Hawaii. The check-out runs have served to identify additional data requirements as well as to indicate some desirable model modifications. An analytical tool is now available for design and performance trade off studies and for comparison of alternative cultivation and harvesting system designs, alternative microalgal species, and the like.

The marine biomass project by General Electric's Reentry Systems Division will provide test facilities where long-term harvestable yield studies with adult kelp plants can be carried out. Design studies and model tests uncovered no feasible modifications to the existing Offshore Test Farm (OSTF) that would satisfy engineering requirements. The Goleta Test Farm was deployed, and 600 adult plants were transplanted from natural beds to the structure by late September. Plans were formulated to design, fabricate, and deploy two nearshore test farms. The Catalina Test Farm was towed from San Pedro to Catalina and mooring, power, and discharge line hook-ups, hemi-dome bag deployment, and operational tests were completed.

Most microalgal research to date has been conducted on scales ranging from small tanks in a laboratory to relatively small outdoor ponds associated with sewage disposal systems. If the production of microalgae is to be seriously considered as a source of renewable energy, the total scale must be increased to thousands and even tens of thousands of hectares. The need for considering a much larger scale precipitated a study of climate, water, and land resources.

The evaluation of climate, water, and land resources provides a preliminary stratification of the Southwest into areas of relative suitability and availability for large-scale microalgae production systems. The stratification, or delineated areas, can be used to select sites for species collection and experimental facilities.

The identification of data sources and data gaps and the preparation of a resource evaluation plan will lead to an efficient and timely assessment of resources in the future, providing information as it is needed for research, system design, and system development.

Each of the primary resource and environmental parameters of significance listed in Table 2-15 has been evaluated. They include prohibitive factors, those factors that eliminate sites from further consideration; factors affecting construction costs; factors affecting operating costs; and factors affecting biomass production efficiency.

Factors that may prohibit microalgae production at a specific location are those related to land and water resources. These include certain land ownerships and uses such as urban/industrial, national parks and monuments, regions exhibiting rugged topography, and locations with no or very limited water supply. The parameters listed in Table 2-15 that will determine the cost of constructing a microalgae system include land ownership, land use/cover, topography, soil characteristics, water supply and demand, water rights, and the hydrologic systems (the geographic location and depth of the water supply). Resource parameters affecting operating costs are related almost exclusively to the cost of pumping and delivering water to the system. Therefore, evaporation rates,

Table 2-15.
Resource and environmental parameters affecting microalgae production systems

Climate	Water	Land
Insolation	Supply	Ownership
Temperature	Demand	Use/Cover
Evaporation Rate	Legal Constraints	Topography
Precipitation	Quality	Soil Characteristics
Severe Storms	Hydrologic System	Geology

precipitation, the depth of the water, and the length of supply lines will all affect operating costs since they determine the equipment and energy requirements for pumping and transporting the water. Climate factors control biomass production efficiency. The conversion of solar energy to bound chemical energy via the photosynthesis process is directly related to insolation and strongly influenced by temperature.

Table 2-16 lists the parameters that were mapped for the southwestern United States and shows the range of values found in this region. The region mapped includes west Texas (west of 100° W. long.), the Oklahoma panhandle, southern Colorado (south of 40° N. lat.), southern California (east of 120° W. long.), and all of New Mexico, Arizona, Utah, and Nevada. Saline groundwater reservoirs with a salinity greater than 3000 ppm were mapped as were areas having a slope less than 10%. Land ownership maps were obtained from federal and state sources. Land use/cover maps were prepared by photointerpretation of some 107 Landsat images. Figure 2-15 is the land use/cover map of Utah.

Table 2-16.
Parameters used in stratifying the Southwest into zones of suitability for microalgae systems

Parameter	Units	Range of Values[a]
Insolation (annual)	kWh/m^2-day	5-5.75
Freeze-Free Period	days	120-300
Evaporation (annual)	centimeters	81-208
Precipitation (annual)	centimeters	10-122
Thunderstorm Days (annual)	days	5-70
Saline Groundwater	mg/L	3000-35,000+
Slope	—	—
Land Ownership	—	—
Land Use/Cover	—	—

[a]These are the ranges of values found in the Southwest.

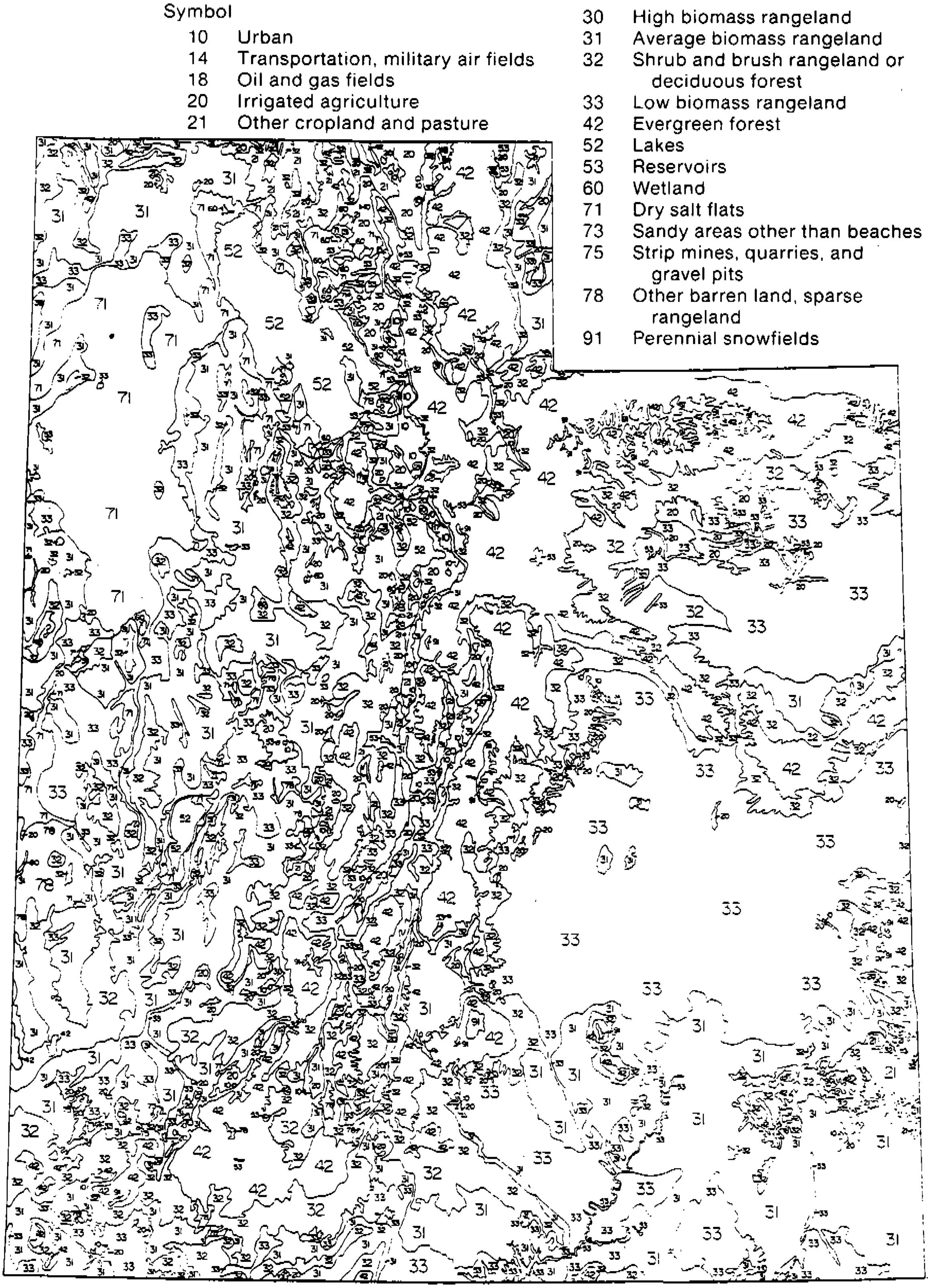

Fig. 2-15. Land use/cover map of Utah

3. Macroalgae

The University of Florida is investigating the cultivation and conversion of marine macroalgae. The technical approach is to maintain 2-m^2 outdoor suspended cultures of Gracilaria and Ulva seaweed with various levels of aeration, water turnover rate, and standing crop density, while continuing bench-scale anaerobic digestion efforts. Investigation of seaweed biomass yields when spray cultured and an economic analysis of generic, land-based seaweed farms also are being carried out.

Gracilaria is routinely maintained in suspended culture by aeration, enhancing growth over that for pond bottom culture. It is, however, a major cost and energy consumer that should be reduced to a minimum level consistent with high yield. Research has shown that intermittent aeration, for as few as 6 hours per day, under two different periodicities, results in the same yields of Gracilaria as does continuous aeration.

Major problems and economic costs of a large-scale seaweed biomass system would be the supply and deployment of essential nutrients to the individual plants and the retention of the enriched water within the area of cultivation long enough for the seaweed to assimilate the nutrients. However, research has shown that nutrient-deficient seaweed is capable of rapidly assimilating and storing inorganic nutrients, which may then be drawn upon for normal growth for periods of days to weeks in the virtual absence of an external nutrient supply. In another series of experiments, the long-term effects of rapid nutrient uptake and storage on growth of the seaweed was examined. The results of this experiment showed that soaking Gracilaria in nutrient-enriched seawater for as few as 6 hours every 2 weeks is sufficient to enable the plants to grow at the maximum possible rate under the conditions of the experiment.

The one factor that has been found to date to be the most important in affecting the growth and yield of Gracilaria is seawater exchange rate (retention time). Since pumping water is a major cost factor in the culture system described here, it would be desirable to achieve the high yields possible at very rapid exchange rates with much less water flow. First, however, it is necessary to understand the relationship between yield and water exchange.

Gracilaria can use little or no bicarbonate, with photosynthesis at pH 9.0 only 19% of that at pH 7.5. Other species of seaweed apparently do utilize bicarbonate readily to continue photosynthesis and growth at high pH. The green alga, Ulva lactuca, was found to produce oxygen at pH 9.1 at a rate of 72% of that at pH 7.5 (versus 19% for Gracilaria). Ulva would thus be an ideal candidate for marine biomass production. It has grown in culture for a year and so may represent an important contribution to the marine biomass field.

Although pulse feeding of seaweed has economic advantages over continuous enrichment of the seawater flowing through the cultures, an enrichment medium made from commercial fertilizers or bulk inorganic chemicals still represents a major cost to the production system. However, where seaweed is digested anaerobically to produce methane, all of the essential nutrients remain in the digester residue or effluent and represent a potential enrichment medium that could be supplied to the production system at little or no cost. The growth of Ulva fed this residue was found to be equal to or better than that for inorganically fed Ulva. Such was not the case for Gracilaria since it is more resistant to digestion than Ulva is. However, growth of Ulva in both media declined due to increasing summer temperatures that proved lethal by mid-July. A more temperature-resistant species is now being sought. Figure 2-16 shows the energy produced as methane per square meter per day from the two residue-fed cultures. Although the yields of Ulva were on average lower than those of Gracilaria, particularly during the latter part of the experiment when Ulva was losing its fight against high temperatures, the energy yield of Ulva was greater, due to its greater digestibility.

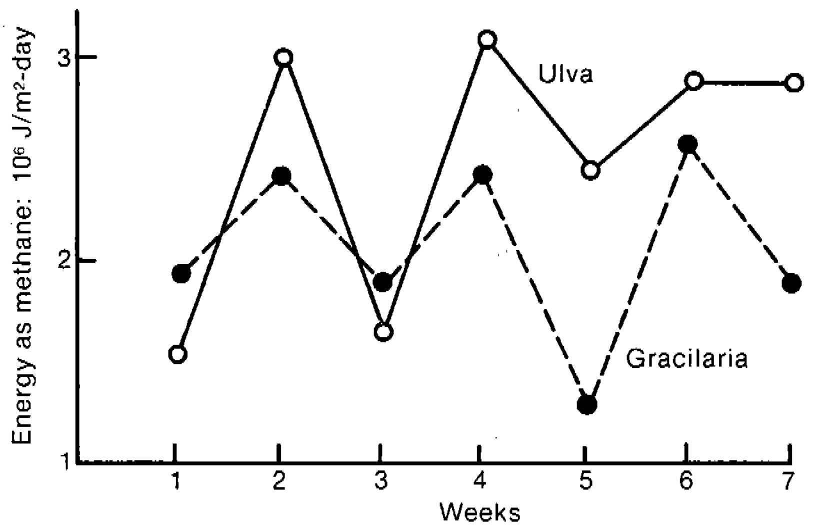

Fig. 2-16. Energy yields as methane produced from cultures grown in recycled digester residues

4. Emergent Plants

The University of Minnesota researches wetland biomass production of cattails (Typha) by incorporating field and laboratory studies into analysis of management options concerning biomass production in both newly established stands and natural stands. Natural stands include areas to be reclaimed following peat mining and stands in wastewater treatment areas. Current research focuses on stand management, harvesting, and evaluation of management options.

The Minnesota research effort has demonstrated that total annual biomass yields between 23 and 27 dry tonnes/ha are possible in planted stands. This compares with yields of total plant material between 8 and 15 dry tonnes/ha in a typical Minnesota corn field. At least 50% of the Typha plant is composed of a belowground rhizome system containing 40% starch and sugar, making rhizomes an attractive feedstock for alcohol production.

Research into Typha stand establishment has been focused on planting material and land preparation schemes. Planting material can be in the form of seed, seedlings, or rhizome pieces. Seed is by far the least costly, but initial results indicate low first-season yields. However, it appears that densities, heights, and yields will be extremely high for the area planted with seed in 1981, which is now being harvested and analyzed. Land preparation studies to test the feasibility of growing crops on mined peatlands involved the excavation of two areas by removing 0.6 m and 1.5 m of peat, and simply rotovating a third area. Excavation proved to be an effective, though costly, weed control method; and the 0.6 m excavation area required the least amount of water control. From preliminary observation, Typha yields will be significantly greater, especially for the replanted seedling plots in the unexcavated area.

Nutrient experiments showed that phosphorus and potassium applications resulted in increased density, and potassium application resulted in increased belowground dry weight. Wetland species comparisons involved Scirpus flaviatiles (rush), Sparganium eurycarpum (bur reed), Spartina pectinata (cordgrass), and Phragmites australis (reed) grown in 36 1.5 m^2 paddies under identical conditions. Scirpus attained the highest first season yields at 12.8 tonnes/ha (total dry weight), as can be seen in Table 2-17.

Table 2-17.
Wetland species comparison: demonstration plots

Excavation Depth (m)	Plant Genus	Dry Weight (tonnes/ha)				Shoot Density (per m^2)
		AG	BG	Total	Competitor	
0.0	Sparganium	6.7	4.0	10.6	0.5	78
0.6	Sparganium	2.5	3.3	5.8	0.0	50
1.5	Sparganium	5.2	4.9	10.1	0.0	73
0.0	Scirpus	7.5	5.3	12.8	1.3	105
0.6	Scirpus	4.7	5.3	9.9	0.0	109
1.5	Scirpus	5.1	3.7	8.8	0.0	94
0.0	Phragmites	0.2	0.2	0.4	6.0	10
0.6	Phragmites	0.4	0.2	0.7	0.6	17
1.5	Phragmites	0.7	0.4	1.1	0.0	70

AG = aboveground BG = belowground

Phragmites performed poorly owing to problems with initial establishment. Typha rhizomes collected from five productive natural stands and a commercial nursery had yields within the range usually found in natural stands with a mean yield of 20.6 tonnes/ha (Table 2-18). Finally, laboratory work on micropropagation resulted in the formulation of Typha implants in tissue culture. Infestation of the Typha crop with canary and reed meadow grass, the primary competitors, was effectively eliminated using 2.3 L/ha of herbicide.

Table 2-18.
Typha planting stock comparison

Source of Planting Stock	Dry Weight (tonnes/ha)				Shoot Density (per m^2)
	AG	BG	Total	Net	
Eagle Lake	11.4±0.6	22.6±0.6	11.6±1.7	23.0±1.7	51.0±5.9
Carlos Avery	9.7±0.9	11.8±2.6	21.5±3.1	20.5±3.1	53.0±7.4
Roseau	9.2±0.9	12.1±1.5	21.3±2.3	20.0±2.3	51.0±4.3
Syre	8.6±0.8	10.7±1.7	19.3±2.2	17.6±2.2	49.0±7.4
Fort Snelling	8.3±0.5	9.7±4.4	18.0±4.8	17.2±4.8	53.0±7.7
Kester	5.9±1.4	7.2±3.0	13.1±4.4	12.8±4.4	46.0±8.9
Entire Population	8.8±1.9	10.5±3.0	19.4±4.5	18.4±4.3	51.0±7.0

AG = aboveground BG = belowground

Research on a water hyacinth wastewater treatment system by Reedy Creek Improvement District (Orlando, Fla.) focuses on rapid evaluations and optimizations of system parameters, optimization of biomass yields, and expansion of biomass yield capacity while maintaining acceptable wastewater treatment standards. Mass and energy balances will be completed to establish a foundation for system optimization and for the economic analysis necessary to determine the potential for commercialization.

The system capacity has been increased by adding two more water hyacinth channels for testing and comparison of the effects of system variables. Despite delays resulting from construction and equipment-delivery problems, mechanical failures, and harvesting data variability, much information has been acquired on system operation and efficiency. The research has demonstrated that mean biomass yields of up to 130 dry tonnes/ha-yr are attainable and that secondary wastewater treatment standards can be met. Table 2-19 shows mean yield data for the three channels with the overall mean values for channels 1, 2, and 3 being 54.4, 55.1, and 95.4 dry tonnes/ha-yr, respectively. These data indicate a dramatic improvement in yield for the longest detention times and shortest harvesting frequency.

Table 2-19.
Water hyacinth project harvesting data summary by channel: total removed, harvest frequency, and mean yield per sample period

Period	Total Wet kg	Mean Harvest Frequency (days)	Mean Yield ± 1 Std. Dev. (Dry tonnes/ ha-yr)	Water Detention Time (days)
Channel 1				
3/17/81 - 5/5/81	41,300	16.3	81.3 ± 16	3.6
5/19/81 - 7/1/81	24,110	14.0	74.4 ± 20	
7/14/81 - 9/28/81	9,590	12.0	32.7 ± 13	
10/8/81 - 11/24/81	10,224	19.5	25.1 ± 6.5	
12/8/81 - 2/18/82	22,139	25.4	60.3 ± 55.1	
Channel 2				
3/24/81 - 5/13/81	35,780	25.0	68.3 ± 22	4.3
5/21/81 - 6/23/81	19,100	10.2	87.8 ± 45.5	
7/6/81 - 9/4/81	16,540	12.0	89.4 ± 57.1	
9/23/81 - 11/12/81	3,433	23.0	9.4 ± 8.7	
12/14/81 - 2/22/82	21,030	51.3	20 ± 24.4	
Channel 3				
5/5/81 - 6/29/81	22,430	7.8	67.4 ± 37.9	No Data
7/9/81 - 8/27/81	17,130	7.0	117 ± 51.3	
9/1/81 - 10/15/81	31,890	8.1	129 ± 80.9	
11/9/81 - 2/2/82	41,480	22.0	68.1 ± 48.2	

Research has also shown the importance of environmental effects on system operations and research planning. For example, seasonal effects on water quality and biomass productivity have been found to be so great that they prevent the comparison of data collected in different seasons and change the effect of covering the system from increased productivity in the winter to destruction of biomass in the summer. Optimum restocking density and harvesting schedules were also found to change markedly from winter to summer. In addition, the significance of certain controllable parameters has been ascertained. For example, biomass productivity is greater for primary than for secondary wastewater treatment but is unaffected by water column height. Pest infestation problems and harvesting technique inadequacies have been identified and alleviated.

F. PRODUCTION ENVIRONMENTAL RESEARCH

Maximization of woody biomass production on nutrient-poor sites using environmentally acceptable management practices is the primary emphasis of field studies sponsored at Oak Ridge National Laboratory. Loblolly pine (Pinus taeda), yellow poplar (Liriodendron tulipifera), and sweetgum (Liquidambar styraciflua) seedlings were machine-planted for a determination of the differences in the survival and growth (including causal physiological processes and soil-plant interrelationships) of these species under various combinations of cultural treatments. One-half of the seedlings of each species bore a mycorrhizal infection induced through the use of vegetative inocula in the nursery. The loblolly pine seedlings were infected by the ectomycorrhizal symbiont Pisolithus tinctorius; the yellow poplar, by the endomycorrhizal symbionts Glomus fasciculatus and G. mosseae, and the sweetgum, by G. mosseae alone. The control seedlings of each species were infected by fungal symbionts endemic to the nursery in which each species was grown. The plantings of each host species and mycorrhizal treatment were divided into nine plots of equal size. A fourth species, black locust (Robinia pseudoacacia), was planted in a similar manner but included only seedlings infected with naturally occurring mycorrhizal symbionts.

Three plots of each host species-mycorrhizal treatment combination received a single application of urea at the rate of 100 kg/ha. Three additional plots of each species-treatment combination received four applications of urea at the rate of 25 kg/ha per application at equal intervals during 1982. The remaining three plots of each species-treatment combination received no fertilizer. These fertilization regimes will be continued yearly for the remainder of this study.

Randomly selected seedlings of each species-treatment combination were harvested in March, May, and August 1982; separated categorically into leaves, stems, and root systems; dried and weighed; and prepared for chemical analysis. These samples were analyzed for total N, P, K, Ca, and Mg. Soil samples were collected monthly from March through October 1982 in each of the yellow poplar plots and analyzed for NO_3 and NH_4. Five water samples were collected in 1982 from each of the lysimeters installed in the center of the plots in 1981 and were analyzed for NO_3, NH_4, P, and Ca. Collectively, these chemical analyses of plant tissue, soil, and water samples will provide insight into the mechanisms and pathways of nutrient movement and availability under the intensive management practices required for the optimization of biomass production on marginal lands.

In addition to continuing the investigations initiated in 1981 and 1982, additional experiments in the remaining years of this study will address the plant physiological and soil-plant nutrient processes that will be considered in the near-term use of marginal land for intensive silviculture. These experiments will consider interactions between processes by which plants acquire and use resources and the biological and physical processes by which nutrients are transformed and cycled within the soil-plant system (Fig. 2-17). The studies will consider the rate and seasonal kinetics of net assimilation; energy allocation during the seasonal growth, storage, and mobilization cycle; growth partitioning; and soil-plant-water relationships.

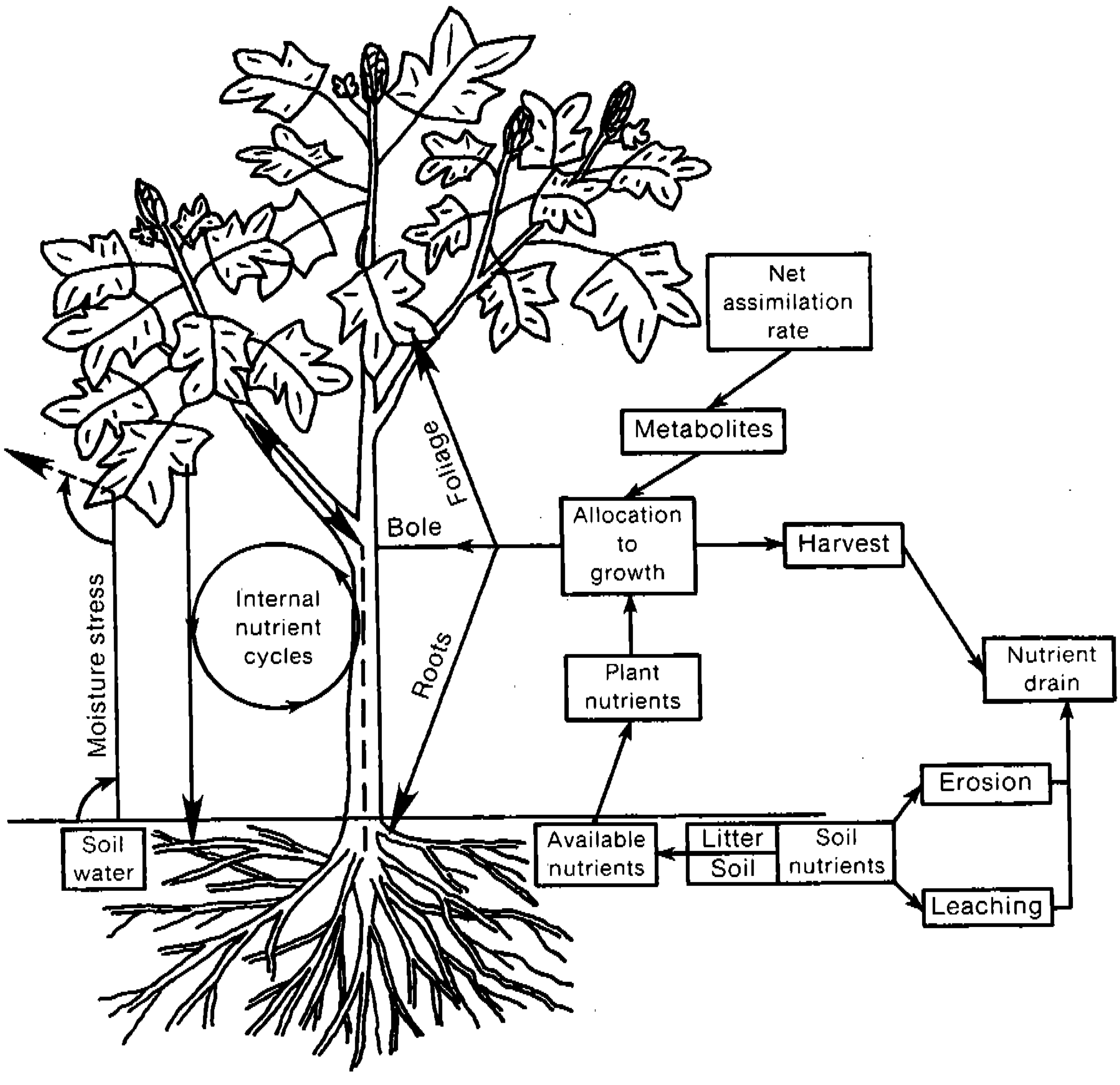

Fig. 2-17. Processes being examined in studies of resource allocation in an intensively managed biomass plantation

Another area of production environmental research at Oak Ridge emphasizes studies on the environmental effects of whole-tree harvesting. This research involves site analysis of residue removal and whole-tree utilization for several forest types on 10 U.S. sites

(Table 2-20). All sites have been dedicated to intensive forestry research for some time, and the effects of whole-tree harvesting are built on a foundation of baseline data. The overall program plan is designed to (1) measure the erosion and nutrient loss from traditionally cut watersheds with and without whole-tree removal and, thereby, quantify the effects residue removal can be expected to have on water quality; (2) quantify the changes in nutrient supply associated with residue removal; (3) assess what these changes mean in terms of subsequent (e.g., in 5 to 10 years) biomass productivity of the areas following the different techniques of harvesting; and (4) identify techniques that can minimize adverse effects of aboveground vegetation removal in hardwood stands. Nutrient studies include measurement of N, K, P, Mg, Ca, and C. The sites for study were selected from geographic regions and locales that are the most heavily forested and harvested areas in the United States. From these areas, specific sites were picked primarily because of the large data bases existing for these forests.

The ultimate goal of this project is to provide information to the timber industry and watershed managers that will assist them in making environmentally sound decisions regarding timber harvest. In those areas of the United States where whole-tree harvesting and residue removal are possible, results from this project can be used to ascertain both short- and long-term consequences of a given harvesting practice. In addition, results from this research can be used to narrow the set of possible negative effects resulting from forest harvesting for a particular region of the United States. Consequently, decisions can be made to ensure long-term forest productivity regarding critical element removal and replacement, practical intensity of harvest, and mitigative harvesting techniques.

By combining total nutrient pools in vegetation, litter, and soils with net changes in nutrients via losses and input, estimates of nutrient depletion for each rotation

Table 2-20.
Sites and forest types included in the whole-tree harvesting research program

Research Group	Site Location	Forest Type
Oak Ridge National Laboratory	Oak Ridge National Environmental Research Park, Tenn.	Mixed upland hardwoods
Southeastern Forest Experiment Station	Coweeta Hydrologic Station, N.C. Holt Walton Experimental Forest, Ga.	Mixed upland hardwoods Slash pine
Northeastern Forest Experiment Station	Mt. Success, N.H. Chesuncook Lake, Maine Cockaponset State Forest, Conn. Hubbard Brook, N.H.	Northern hardwoods Spruce-fir Central hardwoods Northern hardwoods
Clemson University	Clemson, S.C.	Loblolly pine
University of Washington	Charles Pack Forest, Wash.	Douglas fir
University of Florida	Bradford Forest, Fla.	Slash pine

using differing harvesting intensities can be made (Table 2-21). Total-pool values include total soil, litter, and all aboveground vegetation. They do not include belowground roots or stumps because these data are not available. In depletion rate calculations, values for roots and stumps were assumed to be constant. Although it is not possible to determine what portion of the total-soil pool of any nutrient will become available during a single rotation, total-soil measurements provide an upper limit to the soil nutrients potentially available.

By looking at system losses and inputs, regardless of harvesting intensity, it is apparent that K and Ca are the two elements being depleted naturally from most sites. However, total K in soils from most sites is high, thus providing a large reserve. In addition, K and Ca in rock may offset naturally occurring losses of these elements as these materials weather and become part of the soil pool. On the other hand, P pools, which are much lower at most sites, increase as a result of input from rainfall and negligible losses at most sites.

Depletion rates vary widely from site to site for different harvest intensities and for different nutrients. For the five sites for which data are currently available, two show as high as 30% depletion rates of Ca for a single rotation using whole-tree harvesting. Both of these sites, Oak Ridge and Coweeta, are in similar vegetation, mixed upland hardwoods. The Coweeta site shows almost as great a depletion rate with sawlog harvest. Calcium is also being depleted at the Mt. Success, N.H., northern hardwood site but at a much lower rate (4% to 5%). Timber harvest is apparently less of a drain on P and K than on Ca. Because of relatively high rates of input of N (even without considering N fixation), low loss rates, and moderate amounts removed in harvest, N shows low-to-high (1% to 27%) rates of increase, depending on the site and harvest intensity.